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(54) **NANOCRYSTAL-BASED LIGHT SOURCE FOR SAMPLE CHARACTERIZATION**

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F21V 9/32 (2018.01)
F21V 9/38 (2018.01)
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G01N 21/95 (2006.01)

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CPC ***F21V 9/32*** (2018.02); ***F21V 9/38*** (2018.02); ***G01N 21/8806*** (2013.01); *G01N 21/9501* (2013.01); *G01N 2201/061* (2013.01)

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USPC 356/237.1–237.6, 239.1–239.8
See application file for complete search history.

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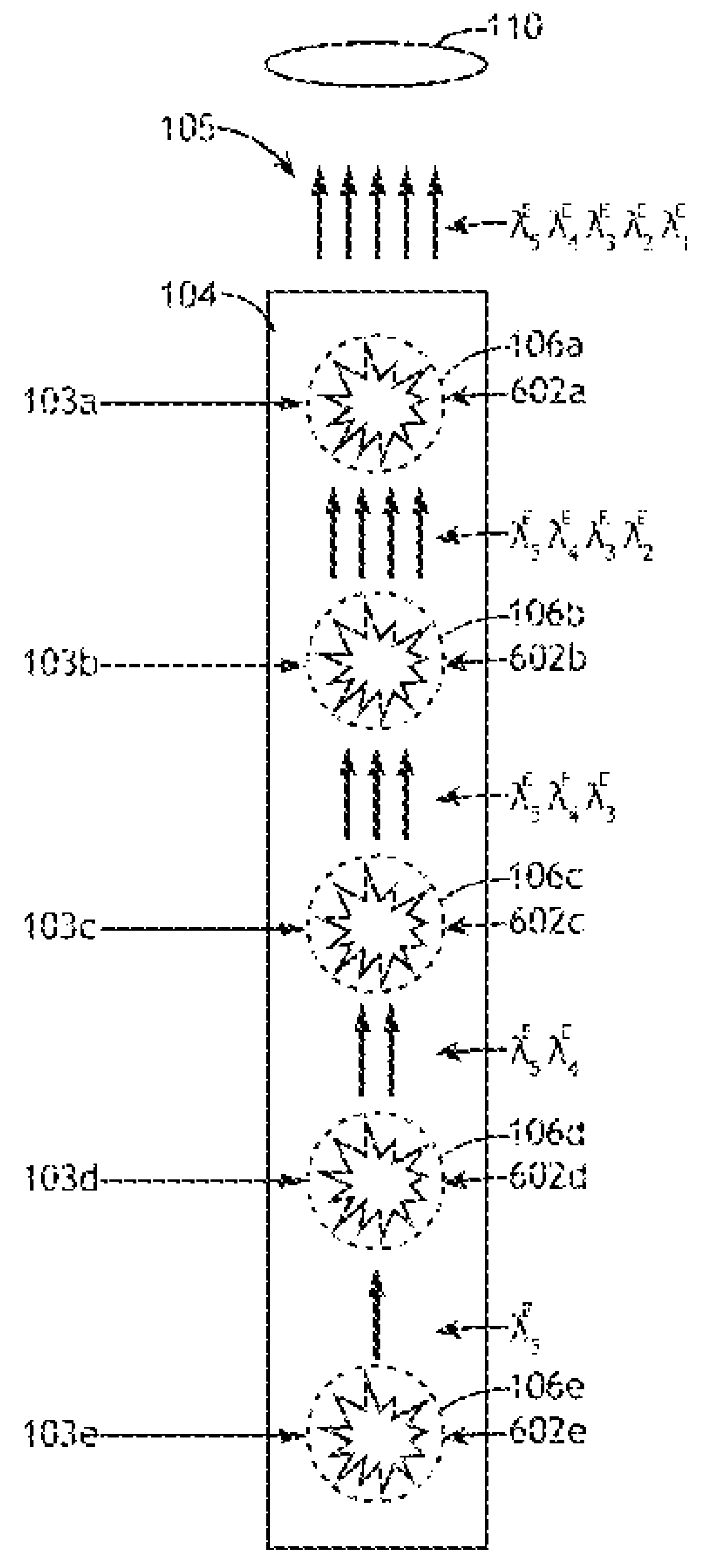
(57) **ABSTRACT**

A broadband illumination source is disclosed. The broadband illumination source may include a pump source configured to generate pump illumination. The broadband illumination also includes an active medium containing nanocrystals. The broadband illumination source includes pump illumination optics configured to direct pump illumination into the active medium. The active medium is configured to emit broadband illumination by down-converting a portion of the pump illumination via photoluminescence.

42 Claims, 16 Drawing Sheets



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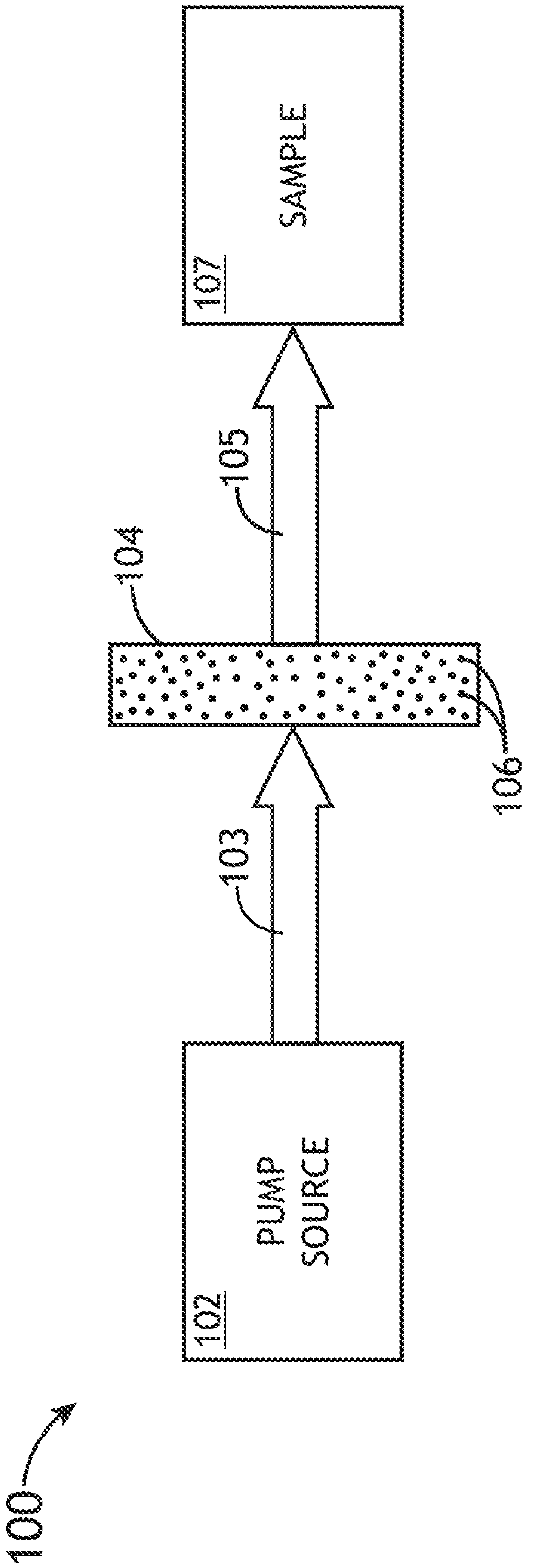


FIG. 1

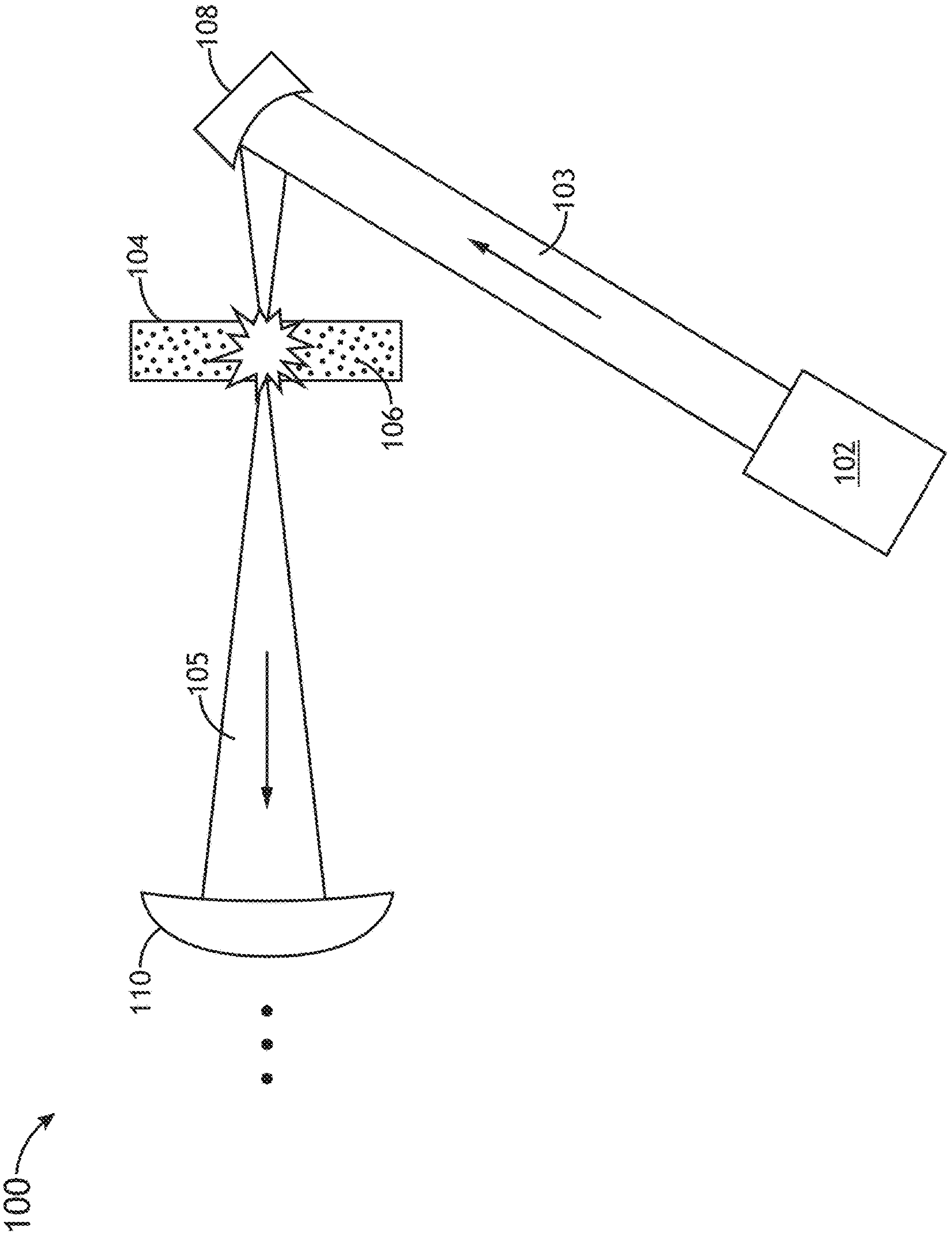


FIG. 2

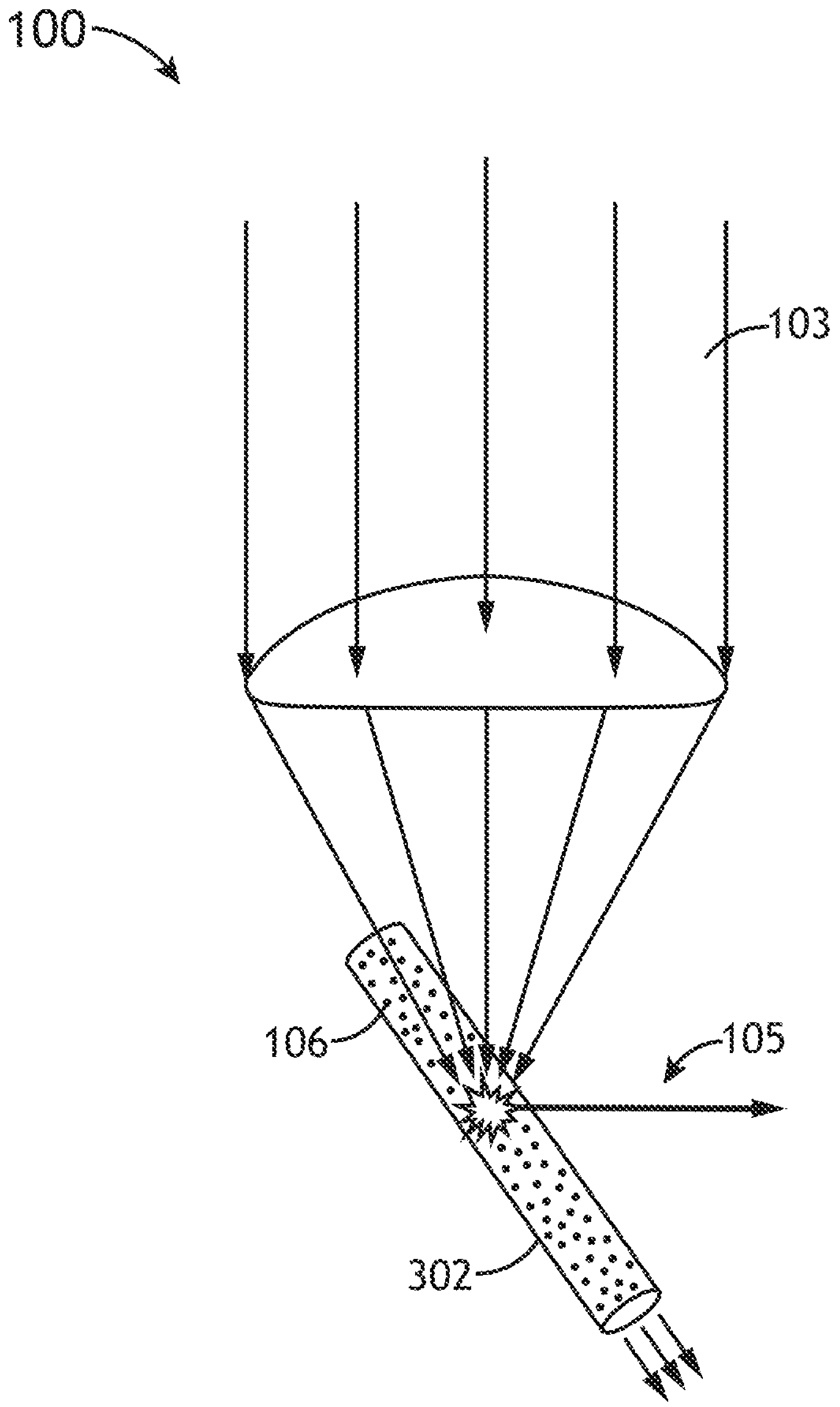


FIG. 3A

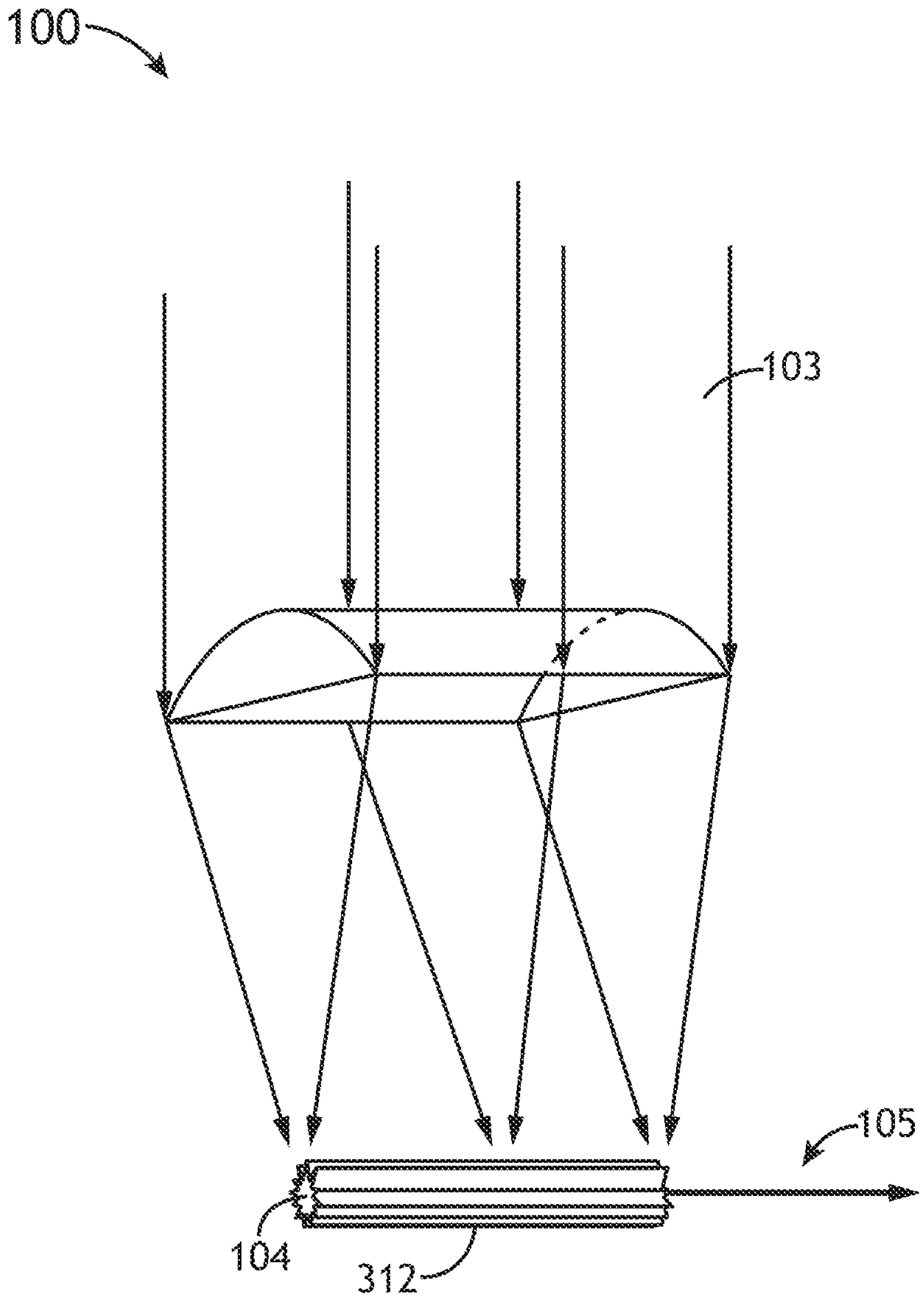


FIG. 3B

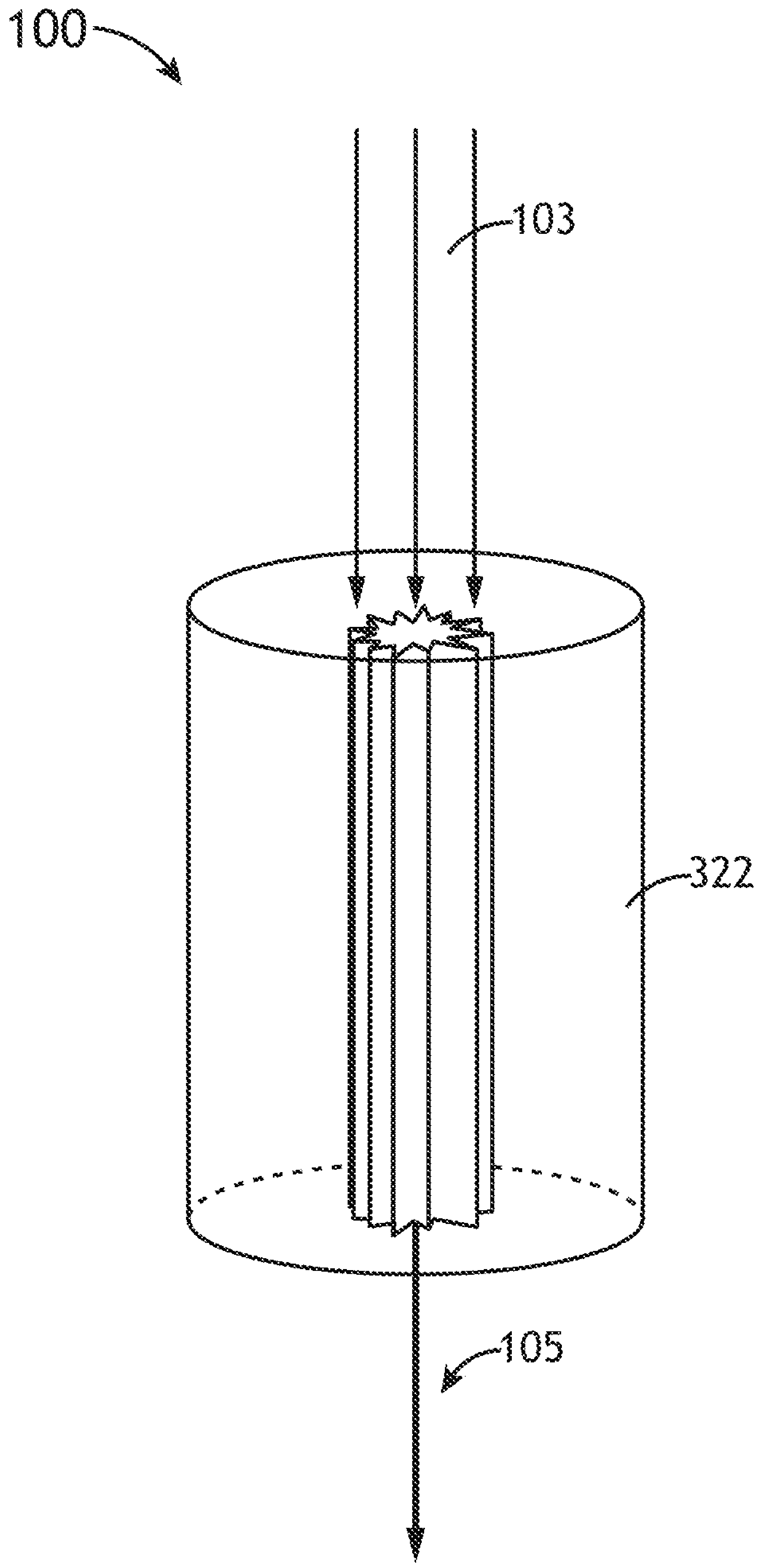


FIG. 3C

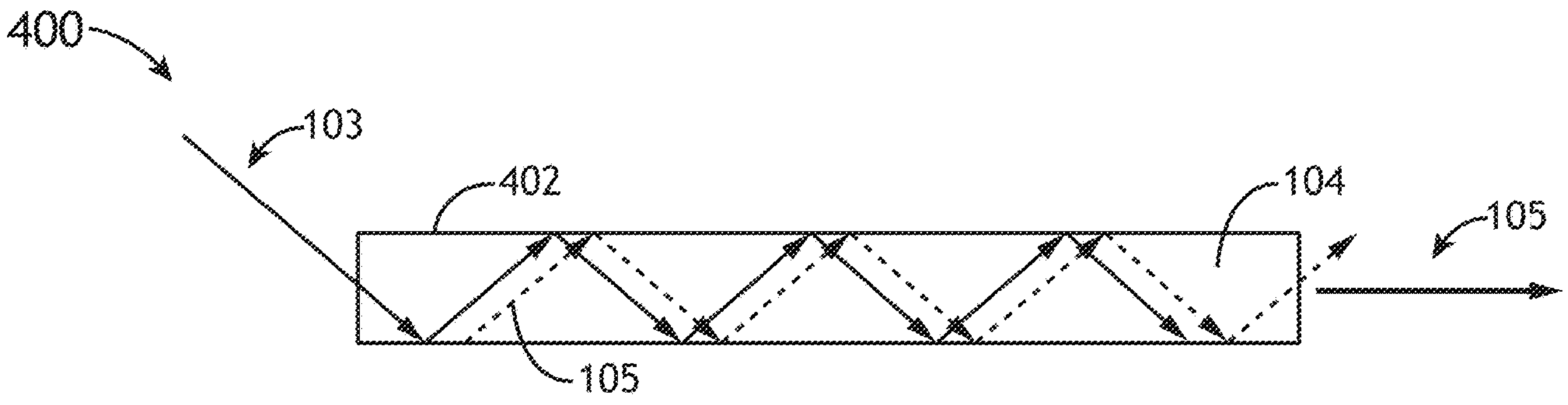


FIG. 4A

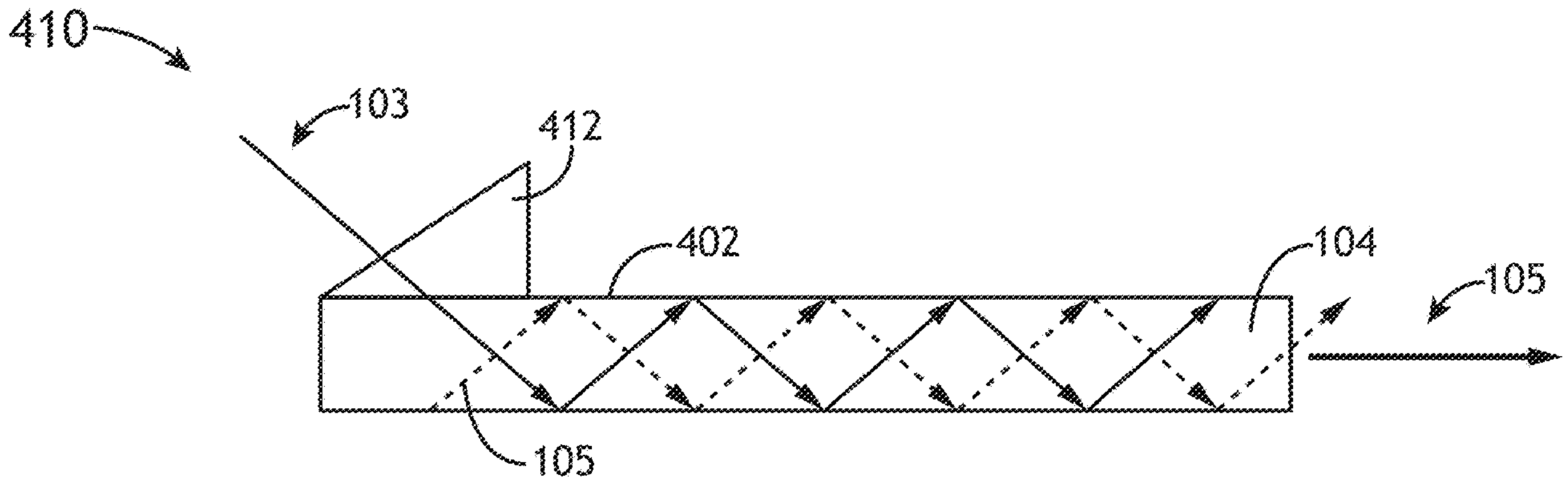


FIG. 4B

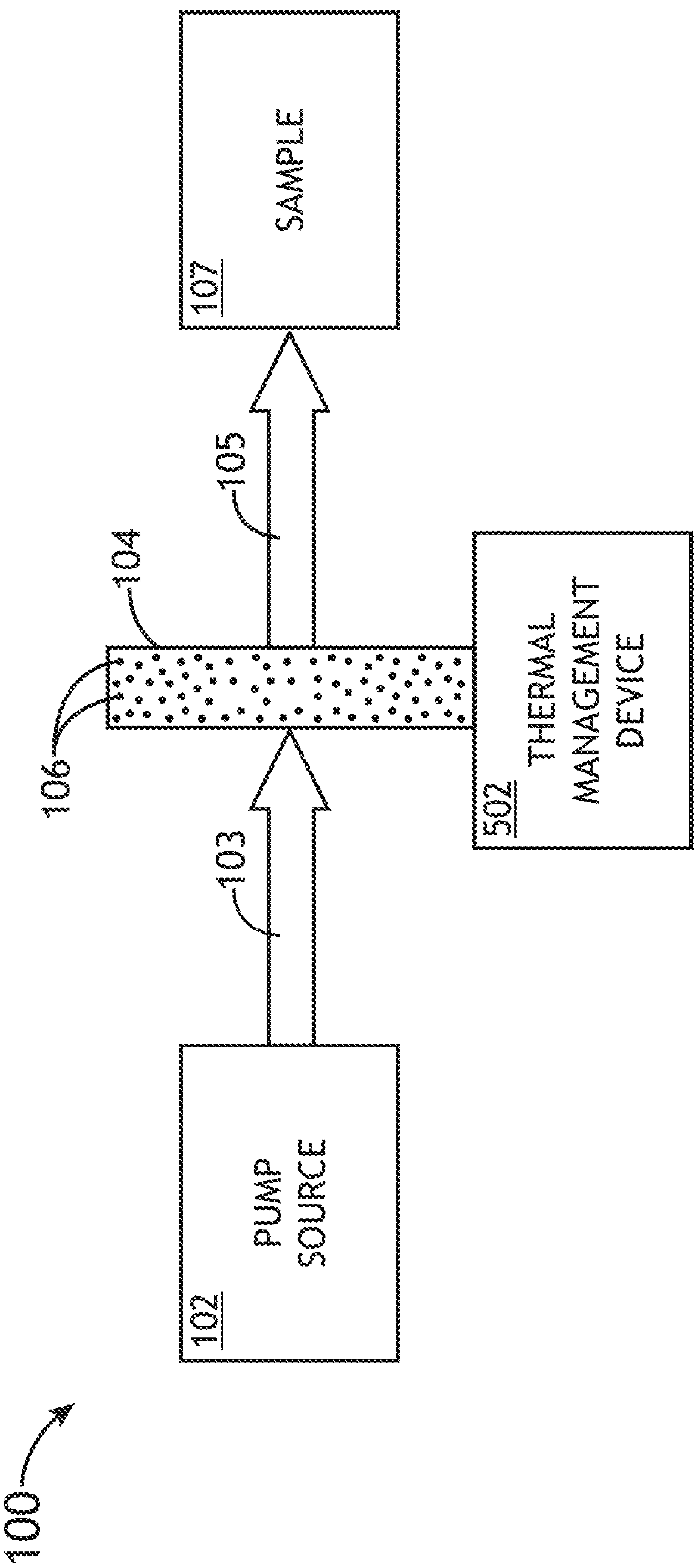

100
102
PUMP SOURCE
103
106
104
105
107
SAMPLE
502
THERMAL MANAGEMENT DEVICE

FIG. 5A

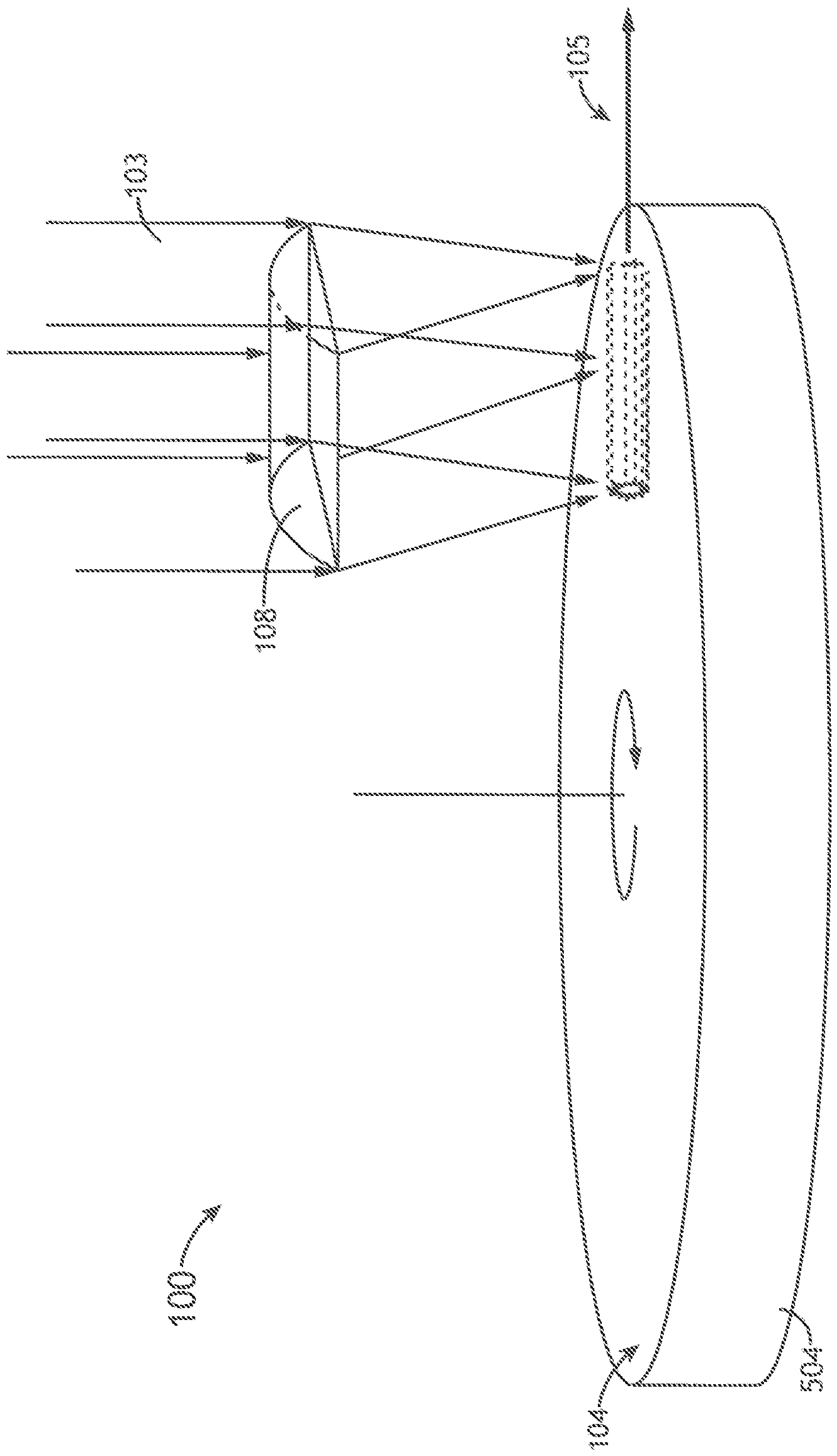


FIG.5B

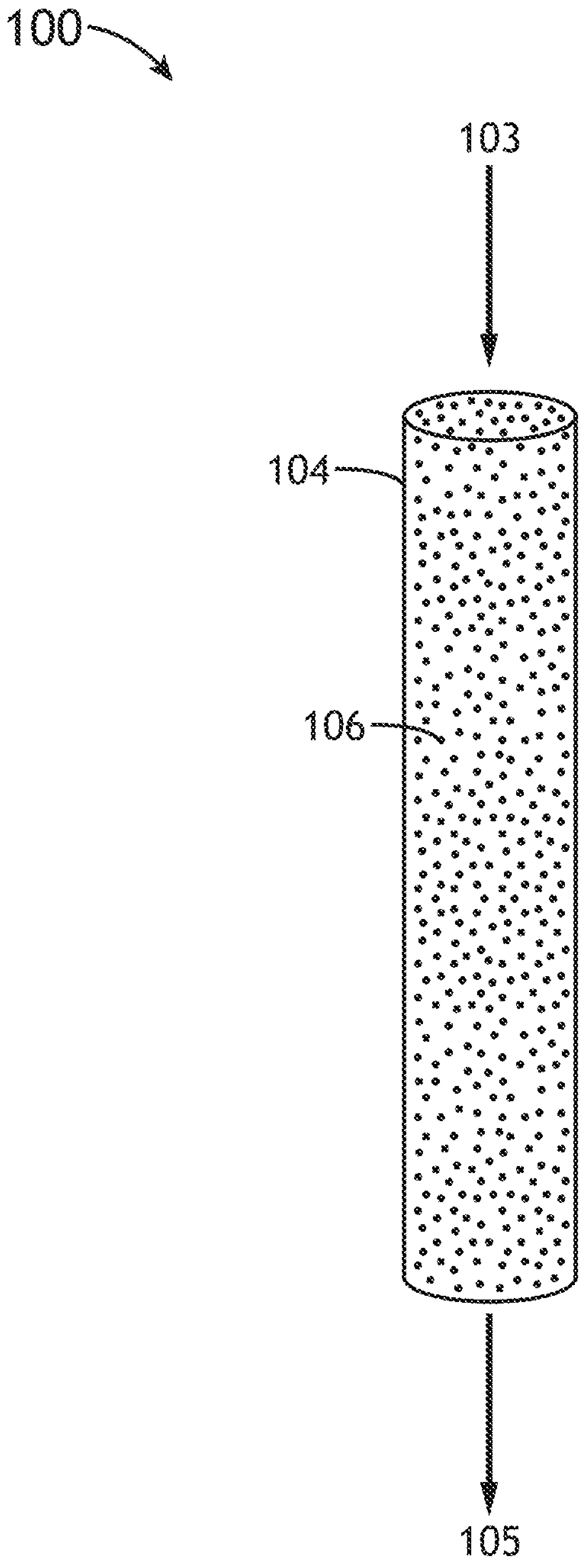


FIG. 5C

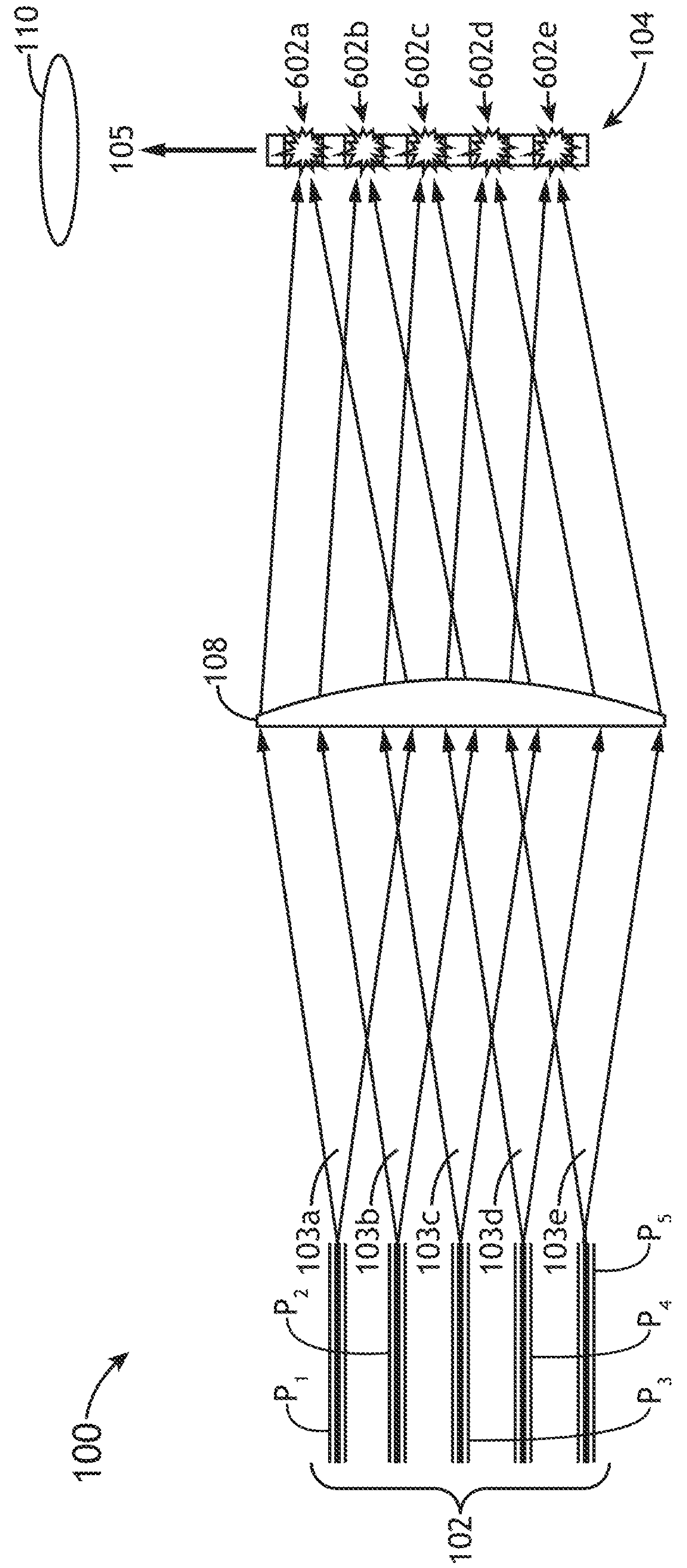

100
102
P1
P2
P3
P4
P5
103a
103b
103c
103d
103e
108
104
105
110
602a
602b
602c
602d
602e

FIG. 6A

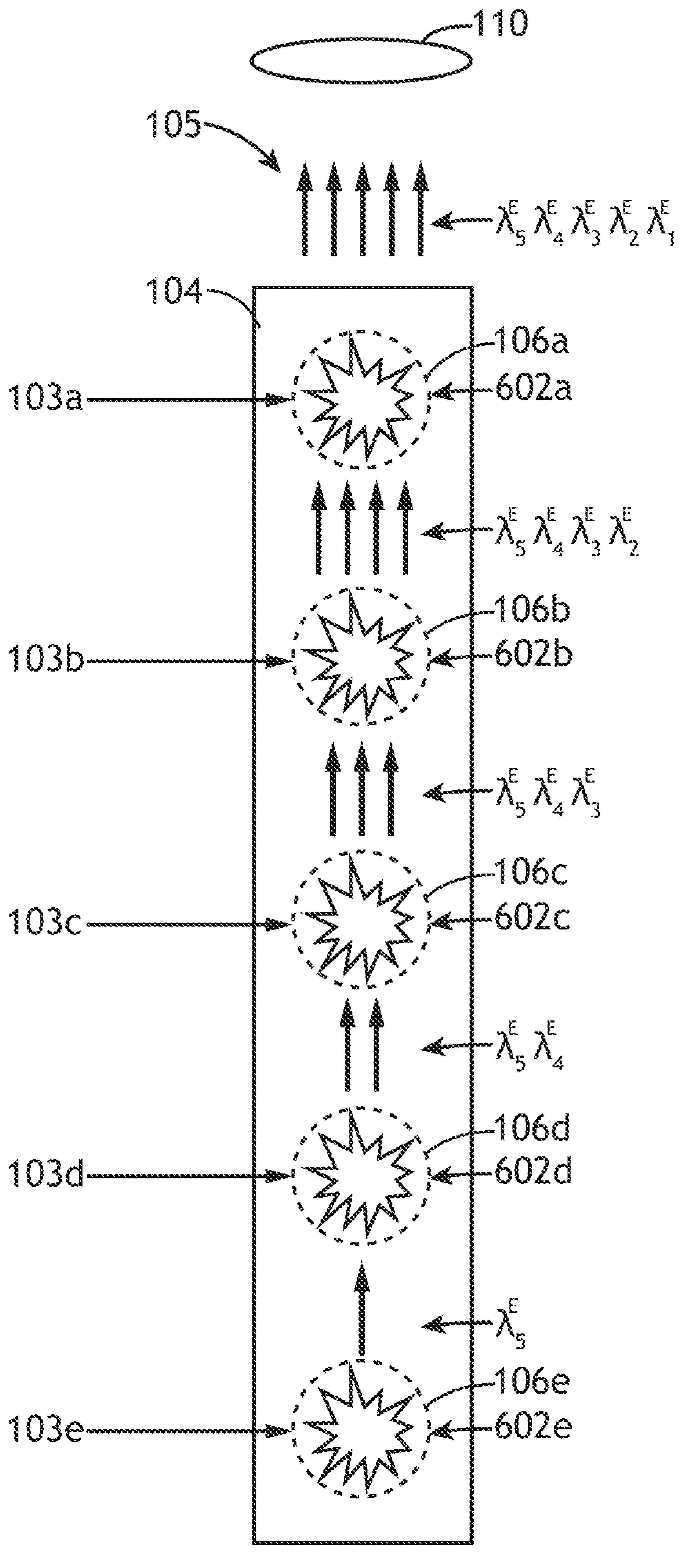

110
105
$\lambda_5^E \lambda_4^E \lambda_3^E \lambda_2^E \lambda_1^E$
104
106a
103a
602a
$\lambda_5^E \lambda_4^E \lambda_3^E \lambda_2^E$
106b
103b
602b
$\lambda_5^E \lambda_4^E \lambda_3^E$
106c
103c
602c
$\lambda_5^E \lambda_4^E$
106d
103d
602d
λ_5^E
106e
103e
602e

FIG.6B

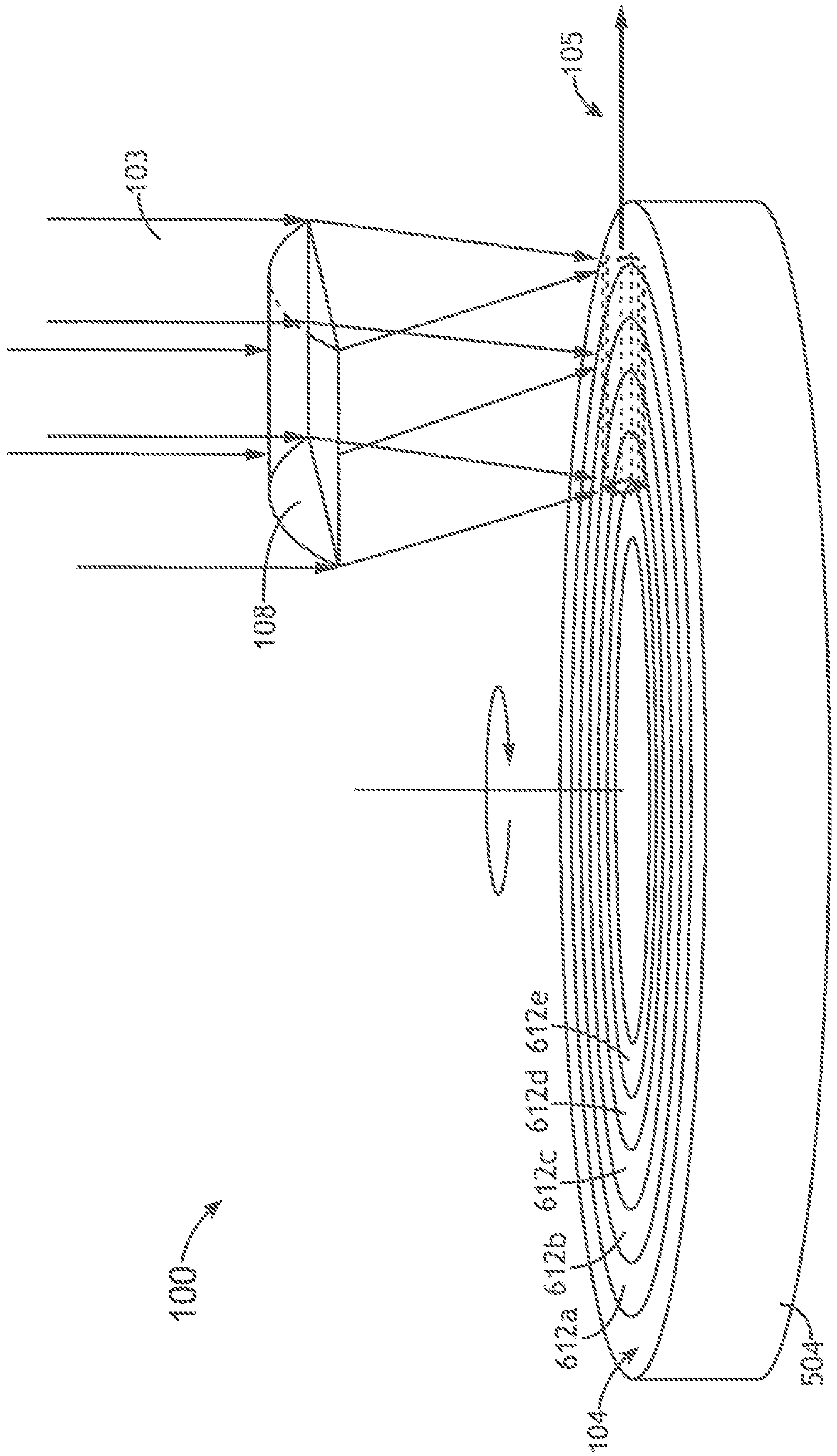


FIG. 6C

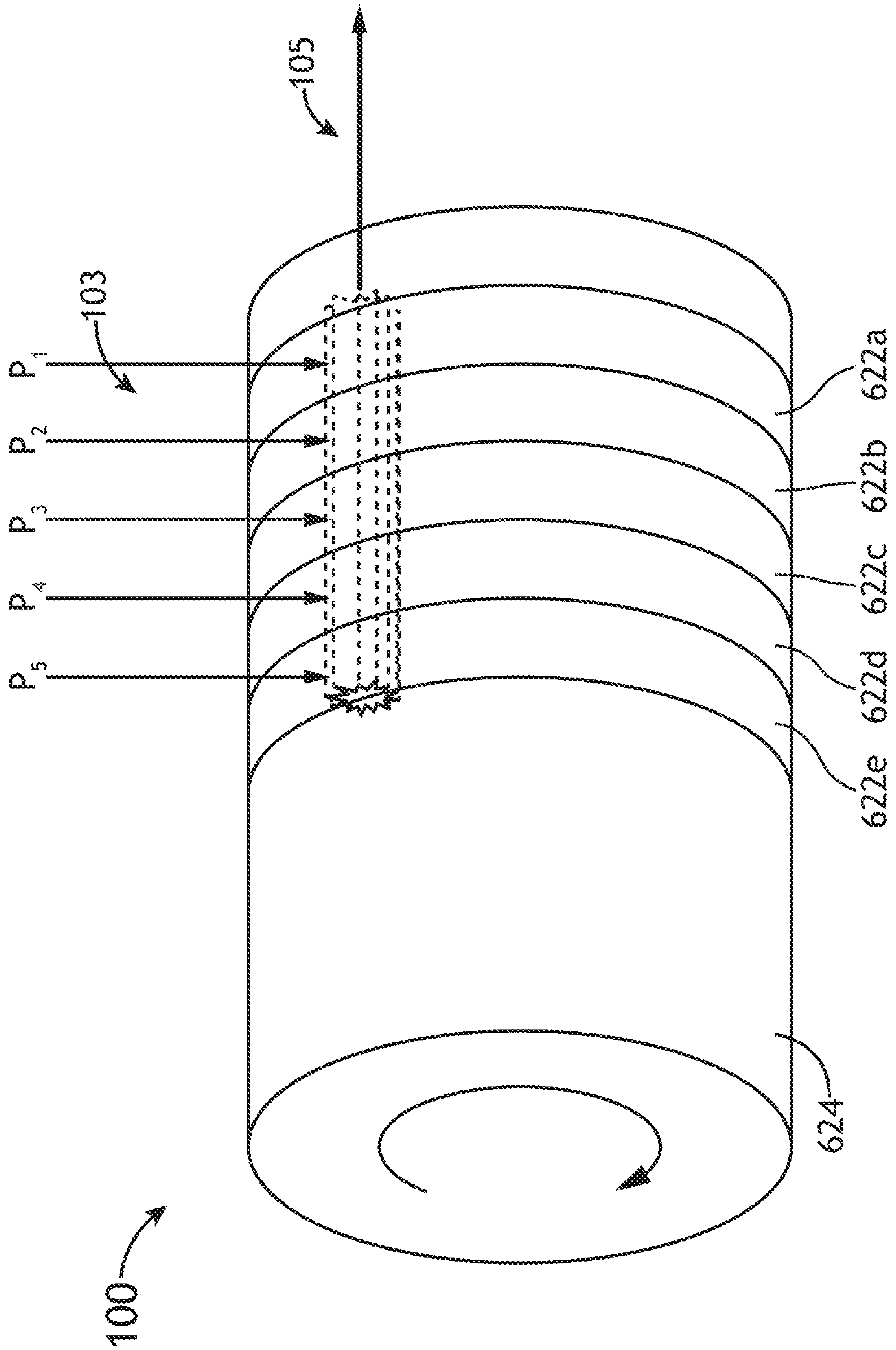


FIG.6D

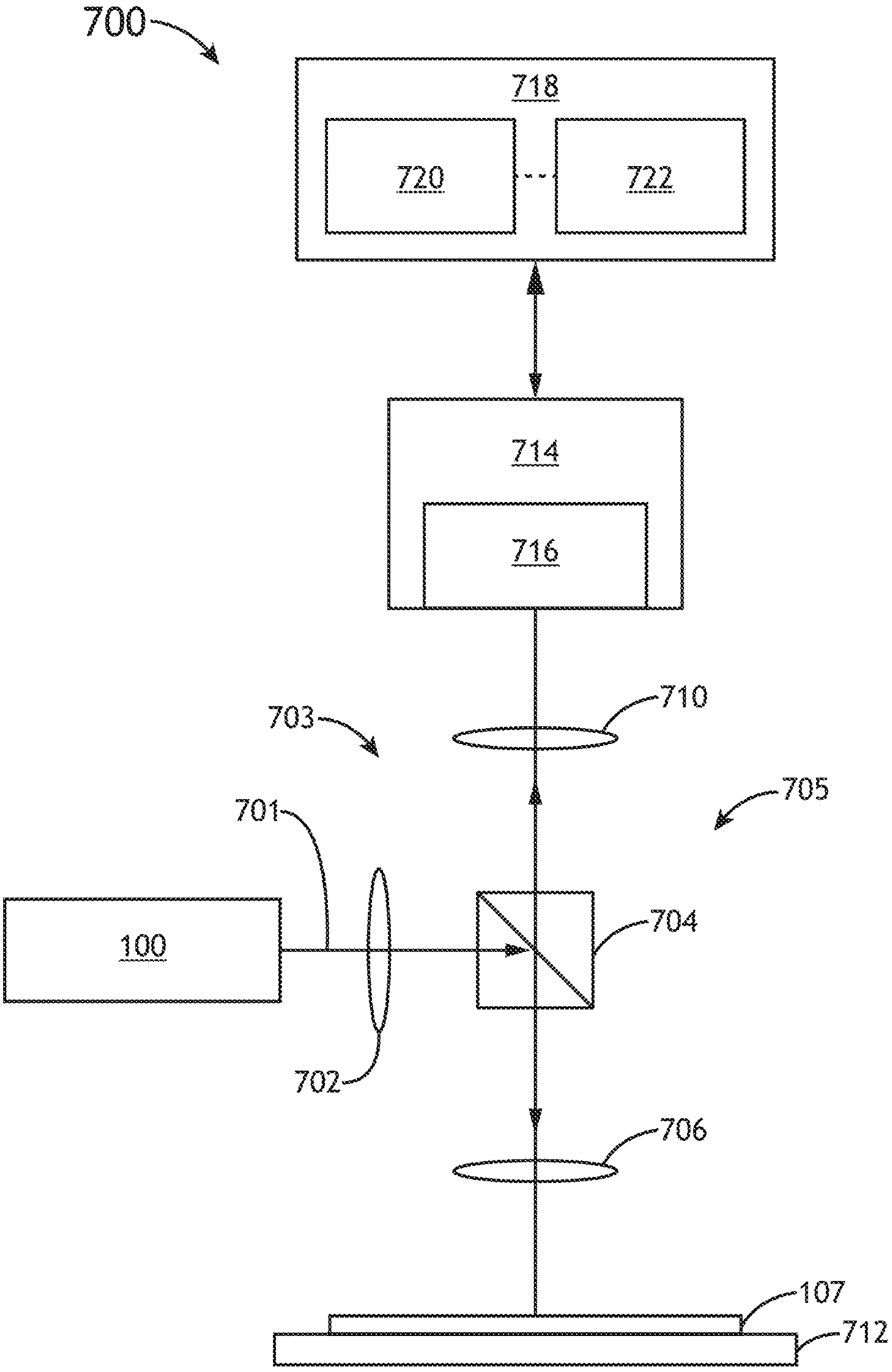
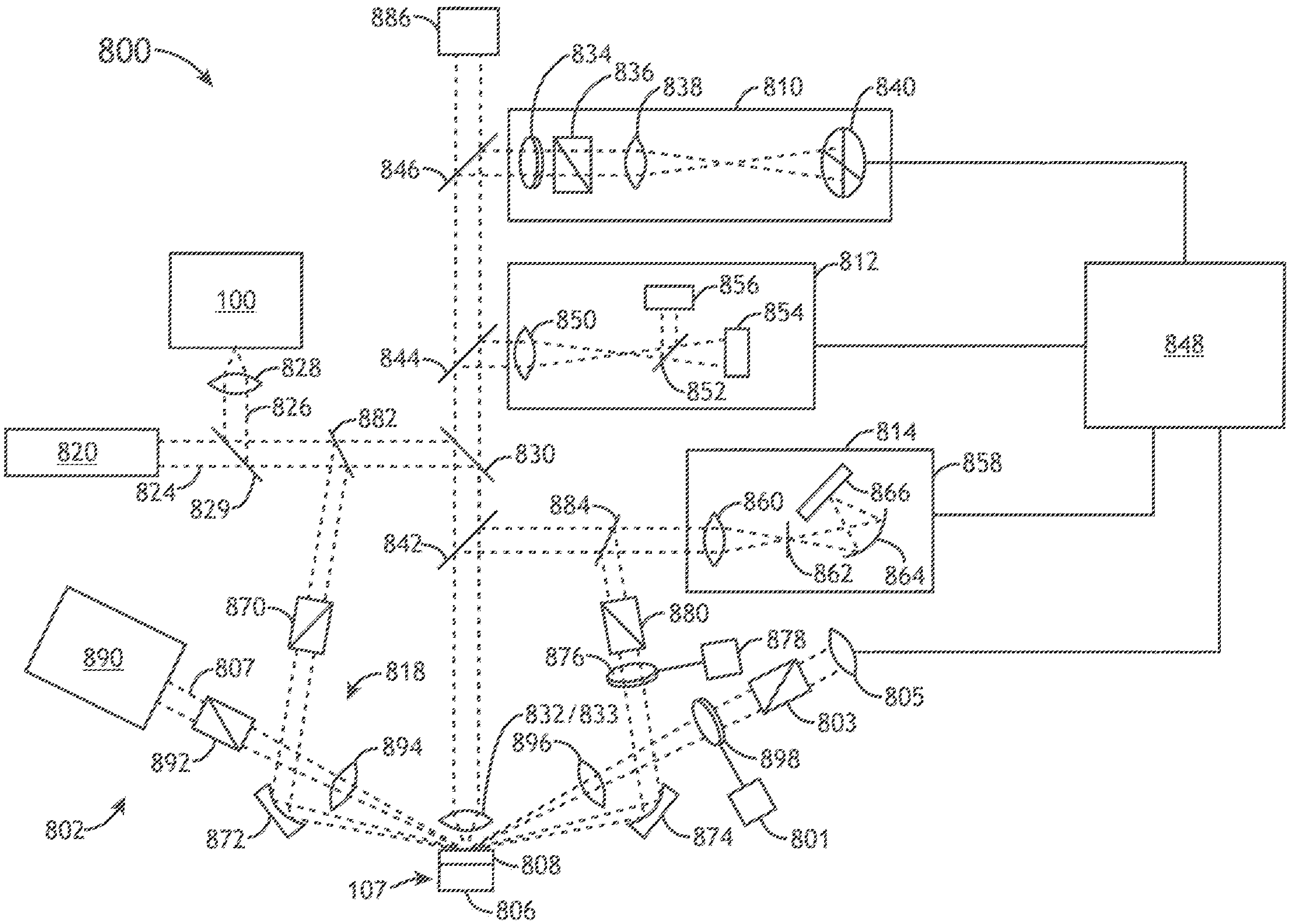


FIG. 7


800
886
834
836
838
810
840
846
100
850
856
812
854
828
844
852
848
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882
820
830
814
824
829
858
866
860
884
842
862
864
870
880
878
890
876
807
818
805
832/833
803
892
896
894
898
802
872
874
801
808
107
806

FIG. 8

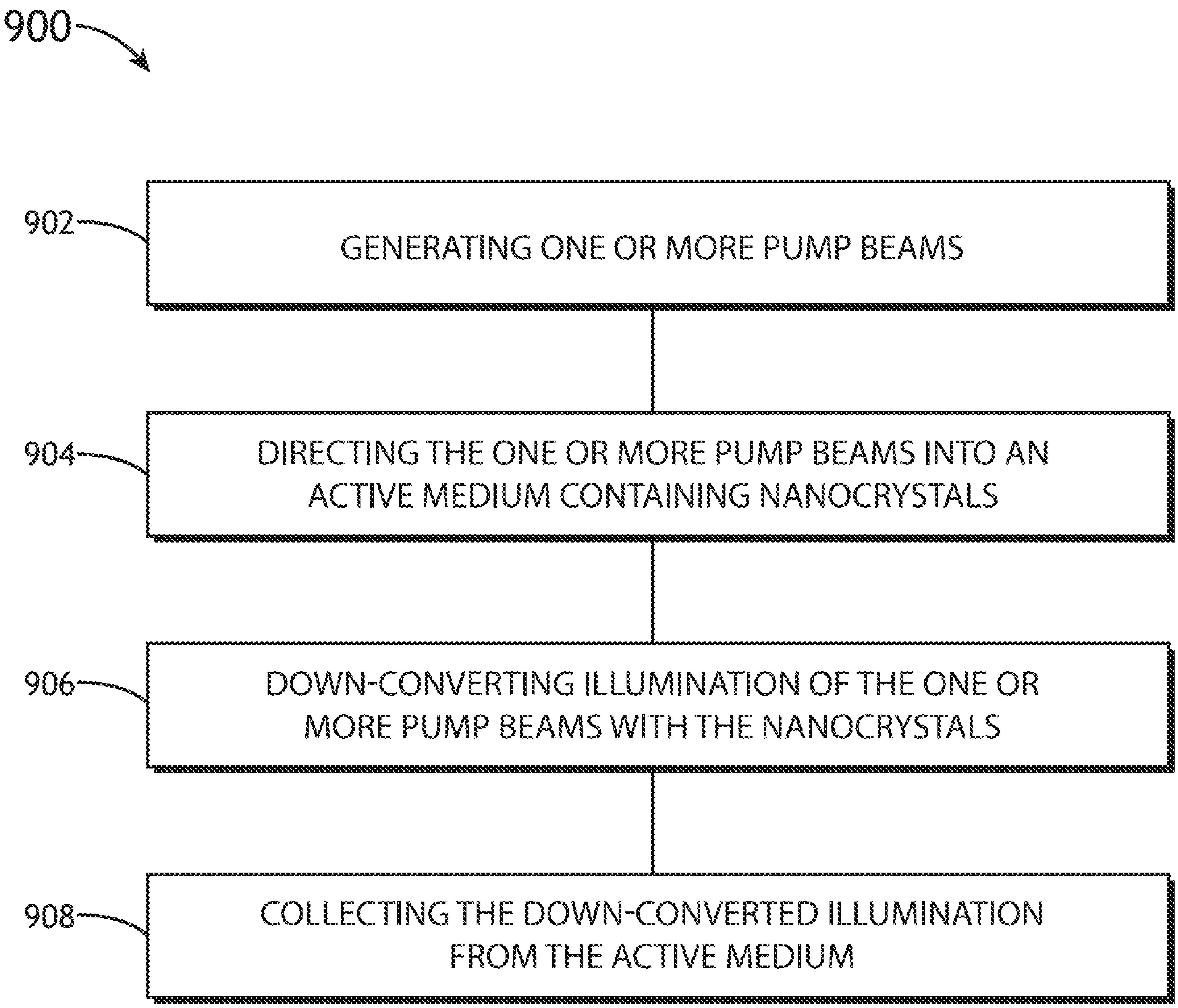
900
902
GENERATING ONE OR MORE PUMP BEAMS
904
DIRECTING THE ONE OR MORE PUMP BEAMS INTO AN ACTIVE MEDIUM CONTAINING NANOCRYSTALS
906
DOWN-CONVERTING ILLUMINATION OF THE ONE OR MORE PUMP BEAMS WITH THE NANOCRYSTALS
908
COLLECTING THE DOWN-CONVERTED ILLUMINATION FROM THE ACTIVE MEDIUM

FIG.9

NANOCRYSTAL-BASED LIGHT SOURCE FOR SAMPLE CHARACTERIZATION

CROSS-REFERENCE TO RELATED APPLICATION

The present application claims the benefit under 35 U.S.C. § 119(e) of U.S. Provisional Application Ser. No. 62/441,881, filed Jan. 3, 2017, entitled NANOCRYSTAL LIGHT SOURCES FOR WAFER INSPECTION, naming Ilya Bezel, Lauren Wilson, Joshua Wittenberg, and Matthew Derstine as inventors, which is incorporated herein by reference in the entirety.

TECHNICAL FIELD

The present invention generally relates to broadband inspection systems, and, in particular, to broadband inspection systems implementing a nanocrystal-based light source.

BACKGROUND

As the density of semiconductor devices increases, so too does the demand for improved illumination sources for semiconductor inspection and metrology techniques and systems. One such illumination source includes a broadband light source. There currently exists a large selection of illumination sources that can be used in the visible and near-infrared spectral regions. Broadband light sources, such as discharge driven or laser-sustained plasma sources, are beneficial for imaging applications in wafer inspection. There are also very bright narrow band sources available in the form of lasers, such as a diode laser. Laser-pumped phosphorous is known to produce stable broadband output in the visible spectral region. Black body emission limits radiance of conventional light sources that rely on heated gas (e.g., plasma) or solid state bodies (e.g., tungsten lamps). In order to achieve the required radiance, temperatures higher than 50,000 K are needed. Radiance of conventional broadband light sources, such as plasma-based sources, is limited by the black-body limit at achievable temperatures. Despite higher temperatures generally achieved in laser-sustained plasmas, their radiance is also not sufficient for many inspection applications. Laser-based sources are not limited by black-body limits and are generally bright, but they typically are narrow band and coherent, which creates certain imaging difficulties, like speckle noise and sensitivity to film thickness, which are often not desirable for wafer inspection. Therefore, there exists a need for an improved broadband illumination source usable in inspection and/or optical metrology systems.

SUMMARY

A broadband illumination source is disclosed, in accordance with one or more embodiments of the present disclosure. In one embodiment, the broadband illumination source includes a pump source configured to generate pump illumination. In another embodiment, the broadband illumination source includes an active medium containing a plurality of nanocrystals. In another embodiment, the broadband illumination source includes one or more pump illumination optics. In another embodiment, the one or more pump illumination optics are configured to direct pump illumination into the active medium. In another embodiment, the active medium is configured to emit broadband illumination by down converting a portion of the pump illumination via photoluminescence.

An optical characterization system for performing inspection and/or metrology of a sample is disclosed, in accordance with one or more embodiments of the present disclosure. In one embodiment, the system includes a broadband illumination source. In another embodiment, the broadband illumination sources includes a pump source configured to generate pump illumination; an active medium containing a plurality of nanocrystals; one or more pump illumination optics configured to direct pump illumination into the active medium, wherein the active medium is configured to emit broadband illumination by down converting a portion of the pump illumination via photoluminescence; and one or more source collection optics configured to collect a portion of the broadband illumination from the active medium. In another embodiment, the system includes a detector assembly. In another embodiment, the system includes a set of characterization optics configured to direct the broadband illumination from the broadband illumination source onto a sample, wherein the set of characterization optics is further configured to direct illumination from the sample to the detector assembly.

A method for generating and using broadband illumination in sample inspection and/or metrology is disclosed, in accordance with one or more embodiments of the present disclosure. In one embodiment, the method includes generating a pump beam. In another embodiment, the method includes directing the pump beam into an active medium containing a plurality of nanocrystals. In another embodiment, the method includes generating broadband illumination by down-converting a portion of the pump illumination with the plurality of nanocrystals via photoluminescence. In another embodiment, the method includes collecting down-converted broadband illumination from the active medium.

It is to be understood that both the foregoing general description and the following detailed description are exemplary and explanatory only, and are not necessarily restrictive of the invention as claimed. The accompanying drawings, which are incorporated in and constitute a part of the specification, illustrate embodiments of the invention and, together with the general description, serve to explain the principles of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

The numerous advantages of the disclosure may be better understood by those skilled in the art by reference to the accompanying figures in which:

FIG. **1** illustrates a conceptual view of a broadband source for generating broadband illumination, in accordance with one more embodiments of the present disclosure.

FIG. **2** illustrates a simplified schematic view of a broadband source for generating broadband illumination, in accordance with one more embodiments of the present disclosure.

FIG. **3**A illustrates a simplified schematic view of a broadband source utilizing a jet of liquid containing nanocrystals suspended as an active medium, in accordance with one more embodiments of the present disclosure.

FIG. **3**B illustrates a simplified schematic view of transversally pumped nanocrystals contained within a capillary structure of the active medium, in accordance with one more embodiments of the present disclosure.

FIG. **3**C illustrates a simplified schematic view of longitudinally pumped nanocrystals contained within a cylindrical volume of the active medium, in accordance with one more embodiments of the present disclosure.

FIG. **4**A illustrates a simplified schematic view of a waveguide arrangement, whereby the pump illumination and the broadband illumination is directed along the elongated active medium, in accordance with one more embodiments of the present disclosure.

FIG. **4**B illustrates a simplified schematic view of a waveguide arrangement including a coupling prism for introducing pump illumination into the active medium, in accordance with one more embodiments of the present disclosure.

FIG. **5**A illustrates a conceptual view of the broadband source equipped with a thermal management device, in accordance with one or more embodiments of the present disclosure.

FIG. **5**B illustrates a simplified schematic view of an active medium containing nanocrystals disposed on a rotatable substrate for thermal management of the active medium, in accordance with one more embodiments of the present disclosure.

FIG. **5**C illustrates a simplified schematic view of a fiber-based active medium containing nanocrystals embedded within the fiber-based active medium, in accordance with one more embodiments of the present disclosure.

FIGS. **6**A-**6**B illustrate a simplified schematic view of a broadband source including a set of lasers used to pump discrete emission regions of an active medium, in accordance with one more embodiments of the present disclosure.

FIG. **6**C illustrates a simplified schematic view of a broadband source including a set of concentric discrete emission regions containing nanocrystals disposed on a rotatable substrate, in accordance with one more embodiments of the present disclosure.

FIG. **6**D illustrates a simplified schematic view of a broadband source including a set of discrete emission regions containing nanocrystals disposed on a rotatable cylinder or drum.

FIG. **7** illustrates a simplified schematic view of an inspection and/or metrology system implementing the broadband illumination source, in accordance with one or more embodiments of the present disclosure.

FIG. **8** illustrates a simplified schematic view of an inspection and/or metrology system implementing the broadband illumination source, in accordance with one or more embodiments of the present disclosure.

FIG. **9** illustrates a flow diagram depicting a method for generating broadband illumination, in accordance with one or more embodiments of the present disclosure.

DETAILED DESCRIPTION OF THE INVENTION

Reference will now be made in detail to the subject matter disclosed, which is illustrated in the accompanying drawings.

The present disclosure relates to improved methods and systems for semiconductor metrology and inspection systems. The following description is presented to enable one of ordinary skill in the art to make and use embodiments of the present disclosure as provided in the context of a particular application and its requirements. As used herein, directional terms such as "top," "bottom," "over," "under," "upper," "upward," "lower," "down," "downward," and the like, are intended to provide relative positions for purposes of description, and are not intended to designate an absolute frame of reference. Various modifications to the described embodiments will be apparent to those with skill in the art, and the general principles defined herein may be applied to other embodiments. Therefore, the present disclosure is not intended to be limited to the particular embodiments shown and described, but is to be accorded the widest scope consistent with the principles and novel features herein disclosed.

Referring generally to FIGS. **1** through **9**, a system and method for the generation of broadband illumination is described, in accordance with one or more embodiments of the present disclosure. Embodiments of the present disclosure are directed toward generating and/or using broadband visible and/or IR radiation (e.g., near IR) in order to inspect, measure, or otherwise image various characteristics (e.g., defects) of a sample (e.g., semiconductor wafer).

FIG. **1** illustrates a conceptual view of a broadband source **100** for generating broadband illumination, in accordance with one more embodiments of the present disclosure.

In one embodiment, the broadband source **100** includes a pump source **102** configured to generate a pump beam **103**. The pump beam **103** is directed to the active medium **104**. In another embodiment, the active medium **104** contains a selected concentration or amount of one or more nanocrystal materials or semiconductor quantum dot materials. For the remainder of the present disclosure, the terms nanocrystals and quantum dots are used interchangeably. In one embodiment, the nanocrystals **106** of the active medium **104** absorb light from the pump beam **103** and down-convert light from the pump beam via one or more photoluminescence processes so as to generate output beam **105** that is red-shifted relative to the input pump beam **103**. It is noted that nanocrystals/quantum dots generally display a short photoluminescence time (i.e., 1-100 ns), high quantum efficiency of photoluminescence, and good stability. By way of example, the nanocrystals **106** contained within a given active medium **104** may down-convert green and/or blue pump illumination **103** into visible and/or NIR broadband illumination **105**. In turn, the down-converted illumination emitted by the active medium **104** may be collected and directed to a sample **107** for purposes of optically characterizing the sample **107**. As discussed in more detail further herein, the broadband output from the active medium **104** may be tuned via the selection of the composition and sizes of nanocrystals **106**.

Although much of the present disclosure is focused on pump illumination in the visible spectrum and a broadband emission in the visible and near-infrared spectrum, these spectral ranges should not be interpreted as a limitation on the scope of the present disclosure. It is noted herein that the scope of the present disclosure may extend to any type (e.g., composition and size) of nanocrystals/quantum dots capable of emitting illumination in any spectral range and a pump source having a spectral range capable of pumping such nanocrystals/quantum dots.

FIG. **2** illustrates a simplified schematic view of the broadband source **100** for generating broadband illumination, in accordance with one more embodiments of the present disclosure. In one embodiment, the broadband source **100** includes one or more pump illumination optics **108** for directing and/or focusing pump illumination **103** from the pump source **102** into the active medium **104**. The pump illumination optics **108** may include any optical element known in the art including, but not limited to, one or more lenses, one or more mirrors, one or more filters, one or gratings, and the like. As depicted in FIG. **2**, a focusing mirror may focus the pump illumination **102** into the volume of the active medium **104**, allowing the nanocrystals **106** to absorb the pump illumination **103**. The nanocrystals **106** may then down-convert light from the pump beam **103** via one or more photoluminescence processes so as to generate the broadband output **105**. In another embodiment, the broadband source **100** includes one or more collection optics **110**. The collection illumination optics **110** may include any optical element known in the art including, but not limited to, one or more lenses, one or more mirrors, one or more filters, one or gratings, and the like. In one embodiment, the one or more collection optics **110** are configured to collect a portion of the broadband illumination emitted from the nanocrystals **106** and direct the broadband illumination to one or more additional optical elements. For example, as discussed further herein, the collection optics **110** of the broadband source **100** may be used to couple the output of the broadband source **100** to the illumination optics of an inspection tool or metrology tool for characterizing the sample **107**.

The pump source **102** may include any illumination source known in the art. In one embodiment, the pump source **102** includes one or more laser sources. For example, the pump source **102** may include, but is not limited to, one or more laser sources configured to emit light between 350-750 nm. For example, pump source **102** may include, but is not limited to, a visible laser source. For instance, the pump source **102** may include, but is not limited to, a laser source configured to emit blue or green light. For instance, the pump source **102** may include a CW laser, such as, but not limited to, a YAG laser (e.g., 532 nm 2nd harmonics of NdYAG laser) or a solid state laser (e.g., GaN laser).

In another embodiment, the nanocrystals contained with the active medium may be selected (e.g., based on composition and/or size) to emit light in the visible and/or infrared (e.g., NIR) wavelength range in response to the pump illumination **103**. For example, the nanocrystal composition may be selected so as to emit visible-NIR light (e.g., 380-2500 nm). For instance, CdSe nanocrystals stimulated by violet or blue visible light (e.g., 380-495 nm) may emit visible and/or NIR light in the 400 to 750 nm range.

It is noted that the scope of the present disclosure is not limited to the down-conversion of pump light or the wavelength range described above. The scope of the present disclosure may be extended to any composition and/or size of nanocrystals capable of emitting illumination in the visible-IR spectrum in response to a pump beam.

In one embodiment, the active medium **104** is a liquid. In this regard, the active medium **104** may include a mixture of the nanocrystals and a liquid material. For example, the nanocrystals and liquid may form a solution, a suspension, or a colloid. For example, the nanocrystals **106** may be suspended in a selected liquid to form the active medium **104**. By way of another example, the nanocrystals **106** may be a colloidal mixture in a selected liquid to form the active medium **104**.

In another embodiment, the active medium **104** is a solid material. For example, the nanocrystals **106** may be formed within a solid matrix within the active medium **104**. The active medium **104** may be formed in any materials processing manner known in the art. In one embodiment, the active medium **104** containing the nanocrystals **106** may be formed via a sol-gel process technique. The fabrication of quantum dots/nanocrystals via sol-gel processing is described in J. Butty et al. "Room temperature optical gain in sol-gel derived CdS quantum dots" *Appl. Phys. Lett.* 69, 3224 (1996), which is incorporated herein by reference.

In another embodiment, the active medium **104** is a glass. For example, the nanocrystals **106** may be formed within a glass matrix within the active medium **104**. In another embodiment, as discussed further herein, a solid or glass active media **104** may be formed on one or more substrates.

It is noted herein that the emission and absorption spectrum of the active medium **104** may be controlled or tuned by the selection of the materials used in the nanocrystals **106** and/or the size of the nanocrystals. In this regard, a particular active medium **104** may be tuned by including nanocrystals **106** from a selected material (or materials) and size (or sizes) to achieve the desired emission spectrum from the active medium **104**.

The active medium **104** may incorporate any type of nanocrystal or quantum dot material known in the art. For example, the nanocrystals **106** used to form the active medium **104** may include, but are not limited to, CdSe, CdS, PbS, ZnSe, and/or CdTe. In another embodiment, the nanocrystals **106** may include core/shell nanocrystals, whereby one material forms the core of the nanocrystal and an additional material forms the shell of the nanocrystal. Core-Shell nanocrystals are particularly useful because they display high photoluminescence quantum yields, stability, large thermal range, and also can be put in various matrices without a large effect on their emission properties. The active medium **104** may incorporate any core-shell or core-shell-shell nanocrystal configuration known in the art. For example, core-shell nanocrystals may be formed from type II-VI; IV-VI; and III-V semiconductor materials (notation is core material-shell material). Such core-shell materials may include, but are not limited to, CdS—ZnS, CdSe—ZnS, CdSe—CdS, InAs—CdSe, PbSe—CdSe. A core-shell-shell configuration may include, but is not limited to, PbSe/CdSe/CdS (i.e., PbSe is core material, CdSe is inner shell material, CdS is outer shell material). It is noted that the listings of core-shell materials and core-shell-shell materials provided above should not be interpreted as limiting in any way on the scope of the present disclosure as it is recognized that any of a number of core material-shell material combinations may be used in the context of the present disclosure.

As noted previously herein, the particular emission and absorption spectrum from the active medium **104** and the nanocrystals **106** may be controlled by controlling the size, and thus the quantum confinement, of the nanocrystals. In one embodiment, the nanocrystals may have an average diameter between approximately 1 and 10 nm. For example, in the case of CdSe, nanocrystals having a diameter of approximately 2 nm may emit blue light, while nanocrystals having a diameter of approximately 8 nm may emit deep red light, with intermediate-sized nanocrystals emitting light between blue light and deep red light. It is noted that this effect is observed in numerous nanocrystal materials across various size ranges and the scope of the present disclosure is not in any way limited to CdSe or the size range 2-8 nm.

In another embodiment, the active medium **104** may contain a mixture of nanocrystal **106** species or may include discrete regions of different types of nanocrystal species.

In some embodiments, the active medium **104** may be formed by fabricating a set of monolayers on a substrate. By way of example, in the case of a set of monolayers, in order to achieve a radiance of 1 W/mm^2/srad/nm, nanocrystals of approximately 10 nm must emit 126 W uniformly in all direction from a 1 mm^2 sample. Such a configuration corresponds to approximately 8×10^{20} photons/s in the 1000 nm wavelength range. If it is assumed that the photoluminescence lifetime is 20 ns and the photoluminescence quantum yield is approximately 50% then approximately 3×10^{13} nanocrystals/mm^2 are needed to achieve the desired radiance. It is noted that nanocrystals can be tightly packed with surface/area densities of approximately 2×10^{12} nanocrystals/mm^2. Therefore, a density on the order of 10^{13} may be achieved by stacking multiple monolayers (e.g., approximately 10 or more), which allows for the desired radiance. It is further noted that the pump power of approximately 0.5 kW/mm^2 is easily achievable with current lasers. It is noted that a liquid active medium may aid in the dissipation of such power. However, solid active media may be suitable, especially in configurations which provide for additional thermal management capabilities as discussed further herein.

Nanocrystals suitable for implementation in the broadband source **100** are described in Riehle, F. S.; Bienert, R.; Thomann, R.; Urban, G. A.; Kruger, M., "Blue luminescence and superstructures from magic size clusters of CdSe" *Nano Lett.* 2009, 9, 514-518; Bruchez, M., Jr.; Moronne, M.; Gin, P.; Weiss, S.; Alivisatos, A. P., "Semiconductor nanocrystals as fluorescent biological labels" Science 1998, 281, 2013-2016; Reiss, Peter; Protière, Myriam; Li, Liang, "Core/Shell Semiconductor Nanocrystals" *Small.* 5 (2): 154-168; Loukanov, Alexandre R.; Dushkin, Ceco D.; Papazova, Karolina I.; Kirov, Andrey V.; Abrashev, Miroslav V.; Adachi, Eiki "Photoluminescence depending on the ZnS shell thickness of CdS/ZnS core-shell semiconductor nanoparticles" *Colloids and Surfaces A: Physicochemical and Engineering Aspects.* 245 (1-3): 9-14; Peng, Xiaogang; Schlamp, Michael C.; Kadavanich, Andreas V.; Alivisatos, A. P. "Epitaxial Growth of Highly Luminescent CdSe/CdS Core/Shell Nanocrystals with Photostability and Electronic Accessibility" Journal of the American Chemical Society. 119 (30): 7019-7029; Makhal, Abhinandan; Yan, Hongdan; Lemmens, Peter; Pal, Samir Kumar "Light Harvesting Semiconductor Core-Shell Nanocrystals: Ultrafast charge transport dynamics of CdSe—ZnS quantum dots" *The Journal of Physical Chemistry C.* 114 (1): 627-632; Smith, Andrew M.; Nie, Shuming "Semiconductor nanocrystals: structure, properties, and band gap engineering" *Accounts of Chemical Research* 43 (2): 190-200; and Murphy, C. J. and Coffer, J. L. "Quantum dots: a primer" *Appl. Spectrosc.* 2002, 56, 16A-27A, which are each incorporated herein by reference in their entirety. Semiconductor nanocrystalline materials are described in U.S. Patent Publication No. 2003/0010987, published on Jan. 16, 2003; and U.S. Pat. No. 8,377,333, issued on Feb. 19, 2013, which are each incorporated herein by reference in their entirety.

FIG. **3**A illustrates a simplified schematic view of the broadband source **100** incorporating a liquid jet **302** as the active medium **104**, in accordance with one more embodiments of the present disclosure. In this embodiment, the liquid-based active medium (e.g., solution, suspension, or colloid) contains nanocrystals **106** and may be flowed along a selected direction in the liquid jet **302**, thereby carrying the nanocrystals through the pump illumination **103**. In turn, the pump illumination **103** may be down-converted by the nanocrystals **106** contained within the liquid jet **302** with the down-converted broadband radiation **105** being emitted along a given collection direction. It is noted that such an arrangement aids in the dissipation of power within the active medium **104**, which provides for thermal management of the source **100**.

In some embodiments, high radiance may be achieved in limited etendue settings through selected configurations of the active media and the pump illumination **103**. In one embodiment, the active medium **104** may be transversely pumped with the pump illumination **103**. For example, pump illumination **103** (e.g., laser beam) may be focused to a line on a surface and/or into a capillary structure containing the active medium. In another embodiment, the active medium **104** may be longitudinally pumped with the pump illumination **103**. For example, pump illumination **103** (e.g., laser beam) may be focused into a cylindrical volume. In these cases, higher radiance may be attained along the longitudinal direction of the pumped volume. Such a configuration provides reduced pump fluence levels, allows for increased volume of the active medium, reduces the thermal load per unit volume of the active medium, and/or aids in the thermal management of the active medium.

FIG. **3**B illustrates a simplified schematic view of transversally pumped nanocrystals contained within a capillary of the active medium, in accordance with one more embodiments of the present disclosure. As shown in FIG. **3**B, pump illumination **103** may be transversely focused/directed into an elongated spot or spots (e.g., forming a line) into a capillary structure **312** or a film structure, which contains the nanocrystals. In this embodiment, the broadband illumination **105** emitted by the active medium **104** may have a higher radiance along the longitudinal direction of the pumped active medium.

FIG. **3**C illustrates a simplified schematic view of longitudinally pumped nanocrystals contained within a cylindrical volume of the active medium, in accordance with one more embodiments of the present disclosure. As shown in FIG. **3**C, pump illumination **103** may be longitudinally focused/directed into a cylindrical volume **322** (or other shape) of the active medium **104**. For instance, the volume of active medium **104** may include a dye-cell containing the nanocrystal-containing active medium **104**. The broadband illumination **105** emitted by the active medium **104** may have a higher radiance along the longitudinal direction of the pumped active medium.

FIGS. **4**A-**4**B illustrate a waveguide arrangement **400**, whereby the pump illumination and the broadband illumination are directed along the elongated active medium **104**, in accordance with one more embodiments of the present disclosure. For example, an active media **104** may be implemented that displays a refractive index sufficient to establish a wave-guide mode within an elongated volume **402** for the selected pump illumination **103**. For instance, as shown in FIG. **4**A, the pump source **102** and the elongated volume **402** of active medium **104** may be arranged such that the pump illumination **103** is coupled into the elongated volume **402**. The elongated volume **402** may include a cylindrical volume of active medium **104**, a capillary structure containing the active medium **104**, or a film of active medium **104**. In this regard, pump illumination **103** of a selected spectral content may be used to pump the active media **104** by exciting one or more wave-guide modes within the active medium **104** having a high-refractive index (e.g., higher than surrounding air or atmosphere). In this embodiment, pump illumination **103** and down-converted broadband illumination **105** emitted by the nanocrystals **106** of the active medium **104** both propagate along the elongated volume **402**.

In another embodiment, as illustrated in FIG. **4**B, the source **100** includes a coupling element **412** arranged to couple the pump illumination **103** into the elongated volume **402** of active medium **104**. It is noted that the pump illumination **103** from the pump source **102** may be coupled into the elongated volume **402** in any manner known in the art. For example, the coupling element **412** may include, but is not limited to, a coupling prism, coupling lens, a coupling grating, and the like. By way of another example, the coupling element **412** may be arranged to couple the pump illumination **103** into the elongated volume **402** at the end of the elongated volume **402** and/or at a side of the elongated volume **402**.

FIG. **5**A illustrates a conceptual view of the broadband source **100** equipped with a thermal management device **502**, in accordance with one or more embodiments of the present disclosure. It is noted that the broadband source **100** may incorporate any device, sub-system, or mechanism suitable for providing thermal management of the active medium **104**. Although various nanocrystals have shown to be resilient at temperatures above 200° C., in some settings thermal management capabilities may be desirable. In some embodiments, the thermal management device **502** may include a mechanical and/or electromechanical device for rotating, translating, or otherwise actuating the active medium **104** such that active medium **104** is moved relative to the pump illumination **103** to mitigate heating caused by the pump illumination **103**. For example, the thermal management device **502** may include, but is not limited to, a movable substrate, whereby the active medium **104** is formed on the surface of or within a layer of the movable substrate.

FIG. **5**B illustrates a simplified schematic view of the broadband source **100** incorporating a rotatable substrate **504** for thermal management of the active medium **104**, in accordance with one more embodiments of the present disclosure. For example, the active medium **104** containing one or more nanocrystal materials **106** may be deposited on a surface of a rotatable substrate **504**, such as, but not limited to, a rotatable disk. For instance, the nanocrystal materials **104** may be deposited on the rotatable substrate **504** via sol-gel processing. In the example depicted in FIG. **5**B, pump illumination **103** may be delivered transversely to a portion of the active medium **104**, providing for the preferential emission of down-converted broadband illumination **105** along the radial direction of the rotatable substrate **504**. It is noted that the rotatable substrate **504** is not limited to a disk structure, which is provided merely for purposes of illustration. It is recognized herein that a mechanical thermal management device **502** may include any type of movable substrate and may come in any number of forms such as, but not limited to, a sphere, a cylinder or drum (see FIG. **6**D), a ring, a conveyor, and the like.

In other embodiments, the thermal management device **502** may include a fluid transport device or sub-system used to flow a fluid active medium, such as a liquid active medium **104**, relative to the pump illumination **103** to mitigate heating caused by the pump illumination **103**. For example, a liquid jet of active medium **104**, such as that depicted in FIG. **3**A, may be used to establish and maintain a flow of active medium **104** relative to the pump illumination **103**. It is further noted that any number of components may be used to establish such a liquid flow of active medium **104**, such as, but not limited to, one or more liquid containers, channeling devices (e.g., tubes, hoses, etc.), pumps, and the like.

FIG. **5**C illustrates a simplified schematic view of a fiber-based active medium **104** containing nanocrystals embedded within the fiber-based active medium, in accordance with one more embodiments of the present disclosure. In one embodiment, the active medium **104** comprises one or more optical fibers impregnated with one or more nanocrystals **106**. In another embodiment, the broadband source **100** may include multiple optical fibers, whereby each fiber (or each grouping of the fibers) is impregnated with a different nanocrystal species. In this example, pump illumination **103** from the pump source (not shown in FIG. **5**C) may be delivered to the nanocrystal-impregnated fiber(s) via a coupling lens (not shown) (or other optical coupling element) used to couple pump illumination from the pump source into a fiber. In another embodiment, a non-impregnated optical fiber (not shown) (or a portion of a single fiber) may deliver the pump illumination **103** to the impregnated optical fiber (or a portion of the single fiber that is impregnated with the nanocrystals).

FIGS. **6**A-**6**B illustrate a simplified schematic view of the broadband illumination source **100** including a set of lasers used to pump discrete emission regions of an active medium, in accordance with one more embodiments of the present disclosure. In one embodiment, as shown in FIG. **6**A, the pump source **102** may include a plurality of laser sources P**1**, P**2**, P**3**, P**4**, P**5** (and so on). For example, each laser may emit pump illumination at a different wavelength. For instance, in the case of laser sources P**1**-P**5**, the pump illumination beams may include pump beams having wavelengths λ^P_1, λ^P_2, λ^P_3, λ^P_4, and λ^P_5 respectively. In another embodiment, each of the pump beams **103***a*-**103***e* may be focused and/or directed via one or more optical elements (e.g., lens, mirror, etc.) into a particular portion of the volume of the active medium **104** so as to create multiple emission regions/spots **602***a*, **602***b*, **602***c*, **602***d*, and **602***e* (and so on). Each emission region may be formed by nanocrystals of a selected nanocrystal species. For instance, each emission region may be formed by nanocrystals of a selected size and/or composition. In another embodiment, each of the emission regions **602***a*-**602***e* may emit illumination of a different wavelength range. For example, the individual pump lasers P**1**-P**5**, the composition of the nanocrystals within each emission region of the active medium, and/or the size of the nanocrystals within each emission region of the active medium **104** may be selected so as to produce the desired output spectrum and/or absorption spectrum for each emission region **602***a*-**602***e*. In this regard, the selection of the pump laser P**1**-P**5***s* wavelengths, the composition of the nanocrystal-based emission regions, and/or the size of the nanocrystals within the emission regions may be controlled so as to tune the output of the emission regions **602***a*-**602***e*.

In another embodiment, the direction of collection of broadband illumination from the emission regions **602***a*-**602***e* may be generally perpendicular to the direction of the pump illumination **103***a*-**103***e* from pump lasers P**1**-P**5**. For instance, in the case where the active medium **104** has an elongated structure (e.g., cylindrical) the pump illumination **103***a*-**103***e* from the pump lasers P**1**-P**5** may be directed to transversely pump the emission regions **602***a*-**602***e*. In another embodiment, each emission region may then emit illumination that is down-converted relative to the respective pump illumination beams **103***a*-**103***e*.

In another embodiment, the emission regions **602***a*-**602***e* (and the volumes of nanocrystal species used to form them) may be arranged such that a first emission region (e.g., **602***a*), which emits a first wavelength or wavelength range, is located on a side of the collecting path nearest the collection optics **110**, where at least an additional region (e.g., **602***b*-**602***e*), which emits an Nth wavelength or wavelength range, is opposite to the first emission region, wherein the Nth wavelength or wavelength range is larger than the first wavelength or wavelength range.

In another embodiment, as shown in FIG. **6**B, each of the nanocrystal species **106***a*-**106***e*, which form the emission regions **602***a*-**602***e*, may be selected such that each successive emissive region is at least partially transparent to the broadband illumination emitted by the previous emission region. In one embodiment, crystal size and/or material composition of the emission regions **602**a-**602**e may be selected in such a way that redder-emitting emission regions are located on the far end of the light collection path and bluer-emitting emission regions are located on the near side of the light collecting path. In such an arrangement, the redder-wavelength light emitted by nanocrystals at the far end propagates through the active media of bluer-wavelength emitting nanocrystals and is not absorbed. In another embodiment, the light propagating in the opposite direction may be absorbed. It is noted that such an arrangement may be fabricated using the same nanocrystal material for each dot and controlling the size of the nanocrystals that make up each dot, with smaller nanocrystals used on the blue-side of the series of dots and larger nanocrystals used on the red-side of the series of dots. In the case of CdSe, it has been shown that a variation in nanocrystal size from 2 to 8 nm causes light emission to vary from violet/blue (on the 2 nm side) to deep red (on the 8 nm side).

For example, as shown in FIG. **6**B, the nanocrystals **106**e used to form emission region **602**e down-convert the pump illumination **103**e of wavelength λ^P_5 to emit broadband illumination having a central wavelength of λ^E_5, where $\lambda^E_5>\lambda^P_5$. The nanocrystals **106**d used to form emission region **602**d down-convert the pump illumination **103**d of wavelength λ^P_4 to emit broadband illumination having a central wavelength of λ^E_4, where $\lambda^E_4>\lambda^P_4$. The nanocrystals **106**d are selected such that the absorption spectrum of the nanocrystals **106**d provides for at least the partial transmission of the broadband illumination containing λ^E_5.

The nanocrystals **106**c used to form emission region **602**c down-convert the pump illumination **103**c of wavelength λ^P_3 to emit broadband illumination having a central wavelength of λ^E_3, where $\lambda^E_3>\lambda^P_3$. In addition, the nanocrystals **106**c are selected such that the absorption spectrum of the nanocrystals **106**c provides for at least the partial transmission of the broadband illumination containing λ^E_4. The nanocrystals **106**b used to form emission region **602**b down-convert the pump illumination **103**b of wavelength λ^P_2 to emit broadband illumination having a central wavelength of λ^E_2, where $\lambda^E_2>\lambda^P_2$. The nanocrystals **106**b may be selected such that the absorption spectrum of the nanocrystals **106**b provide for at least the partial transmission of the broadband illumination containing λ^E_3. The nanocrystals **106**a used to form emission region **602**a down-convert the pump illumination **103**a of wavelength λ^P_1 to emit broadband illumination having a central wavelength of λ^E_1, where $\lambda^E_1>\Delta^P_1$. The nanocrystals **106**a may be selected such that the absorption spectrum of the nanocrystals **106**a provide for at least the partial transmission of the broadband illumination containing λ^E_2. Such an arrangement may result in a collected broadband illumination output **105** that contains illumination generated by each of the emission regions **602**a-**602**e, resulting in an emission spectrum having a spectral content of at least λ^E_1, λ^E_2, λ^E_3, λ^E_4, and λ^E_5. In one embodiment, the nanocrystals **106**a used to form emission region **602**a may be selected such that λ^E_1 is on the bluer end of the spectrum, while nanocrystals **106**e used to form emission region **602**e such that λ^E_5 is on the redder end of the spectrum (relative to λ^E_1). For example, $\lambda^E_1<\lambda^E_2<\lambda^E_3<\lambda^E_4<\lambda^E_5$. It is noted herein that such an arrangement is made possible due to the tunability of the emission and absorption spectra of the emission regions **602**a-**602**e (or any other arrangement) through the selection of the nanocrystal materials and the control of the quantum confinement/sizes of the nanocrystals.

It is noted that, while multiple laser sources P**1**-P**5** are depicted in FIGS. **6**A and **6**B, this arrangement should not be interpreted as a limitation on the scope of the present disclosure and is provided merely for illustrative purposes. For example, the pump illumination **103** used to pump different color emission regions **602**a-**602**e may be provided via a single laser or multiple lasers.

It is further noted that the particular geometry depicted in FIGS. **6**A-**6**B should not be interpreted as a limitation on the scope of the present disclosure and is provided merely for illustrative purposes. It is noted that the scope of the present disclosure should be interpreted to extend to any arrangement of one or more pump sources **102** and emission regions providing for the tunability of emission outputs and absorption spectrums of individual emission regions, through the combination of multiple nanocrystal species (composition and/or size of nanocrystals). Such arrangements may include any arrangement of dots (as in FIGS. **6**A-**6**B), other geometric shapes (e.g., cylinders, rods, pillars), or shells, rings, or layers (e.g., shells or layers of a cylindrical, spherical, or disk structure).

FIG. **6**C illustrates a simplified schematic view of the broadband source **100** including a set of concentric discrete emission regions containing nanocrystals disposed on a rotatable substrate **504**, in accordance with one more embodiments of the present disclosure. In this embodiment, the set of emission regions **612**a-**612**e are arranged concentrically. For example, each emission region **612**a-**612**e may be formed from nanocrystals that cause the emission regions **612**a-**612**e to emit illumination at different wavelengths, whereby emission region **612**e is surrounded by emission region **612**d, emission region **612**d is surrounded by emission region **612**c, emission region **612**c is surrounded by emission region **612**b, and emission region **612**b is surrounded by emission region **612**a. The emission regions **612**a-**612**e may be formed in any manner known in the art. For example, each of the emission regions may be formed on the substrate **504** via sol-gel processing such that each region includes different nanocrystal species, which are tuned to create the desired emission and absorption characteristics for the desired concentric regions.

In another embodiment, the pump source **102** and pump illumination optics **108** are arranged to illuminate the emission regions **612**a-**612**e. As in the embodiment depicted in FIGS. **6**A-**6**B, the pump source **102** may include single or multiple lasers. In one embodiment, a single laser beam may be used to illuminate the emission regions. In another embodiment, multiple lasers may be used to illuminate the different emission regions **612**a-**612**e. It is noted that the embodiments related to the tunability of the emission regions **602**a-**602**e discussed previously herein should be interpreted to extend to the configuration depicted in FIG. **6**C.

In one embodiment, each of the nanocrystal species used to form the emission regions **612**a-**612**e may be selected such that each successive concentric emission region is at least partially transparent to the broadband illumination emitted by the previous inner emission region. In one embodiment, the size and/or material composition of the emission regions **612**a-**612**e may be selected in such a way that redder-emitting emission regions are located in the center area of the substrate **502** and bluer-emitting emission regions are located toward the outer edge of the substrate **502**. In such an arrangement, the redder-wavelength light emitted by nanocrystals at the center of the substrate **502** propagates through the active media of bluer-wavelength emitting nanocrystals.

Although this embodiment is described in the context of rotatable substrate **504**, described previously herein, the scope of the present disclosure is not limited to such a configuration. The embodiment depicted in FIG. **6**C may be extended to any substrate configuration that allows for the formation of successive emission regions of different nanocrystals. For example, as illustrated in FIG. **6**D, the broadband source **100** may include, but is not limited to, a set of discrete emission regions **622***a*-**622***e* formed within an active medium containing nanocrystals disposed on a rotatable cylinder or drum **624**.

FIG. **7** illustrates a simplified schematic diagram of an optical characterization system **700**, in accordance with one or more embodiments of the present disclosure. The optical characterization system **700** may comprise an inspection system and/or a metrology system. System **700** may be configured to perform inspection, optical metrology and/or any form of imaging on a sample **107**. Sample **107** may include any sample known in the art including, but not limited to, a wafer, a reticle, a photomask, and the like. It is noted that system **700** may incorporate one or more of the various embodiments of the broadband source **100** described throughout the present disclosure. In one embodiment, system **700** includes the broadband illumination source **100**, an illumination arm **703**, a collection arm **705**, a detector **714**, and a controller **718** including one or more processors **720** and memory **722**.

In one embodiment, sample **107** is disposed on a stage assembly **712** to facilitate movement of sample **107**. Stage assembly **712** may include any stage assembly **712** known in the art including, but not limited to, an X-Y stage or an R-θ stage. In another embodiment, stage assembly **712** is capable of adjusting the height of sample **107** during inspection or imaging to maintain focus on the sample **107**.

In another embodiment, the illumination arm **703** is configured to direct illumination **701** from the broadband source **100** to the sample **107**. The illumination arm **703** may include any number and type of optical components known in the art. In one embodiment, the illumination arm **703** includes one or more optical elements **702**, a beam splitter **704**, and an objective lens **706**. In this regard, illumination arm **703** may be configured to focus illumination **701** from the illumination source **100** onto the surface of the sample **107**. The one or more optical elements **702** may include any optical element or combination of optical elements known in the art including, but not limited to, one or more mirrors, one or more lenses, one or more polarizers, one or more gratings, one or more filters, one or more beam splitters, and the like.

In another embodiment, system **700** includes a collection arm **705** configured to collect light reflected, scattered, diffracted, and/or emitted from sample **107**. In another embodiment, collection arm **705** may direct and/or focus the light from the sample **107** to a sensor **716** of a detector assembly **714**. It is noted that sensor **716** and detector assembly **714** may include any sensor and detector assembly known in the art. The sensor **716** may include, but is not limited to, a CCD sensor or a CCD-TDI sensor. Further, sensor **716** may include, but is not limited to, a line sensor or an electron-bombarded line sensor.

In another embodiment, detector assembly **714** is communicatively coupled to a controller **718** including one or more processors **720** and memory **722**. For example, the one or more processors **720** may be communicatively coupled to memory **722**, wherein the one or more processors **720** are configured to execute a set of program instructions stored on memory **722**. In one embodiment, the one or more processors **720** are configured to analyze the output of detector assembly **714**. In one embodiment, the set of program instructions are configured to cause the one or more processors **720** to analyze one or more characteristics of sample **107**. In another embodiment, the set of program instructions are configured to cause the one or more processors **720** to modify one or more characteristics of system **700** in order to maintain focus on the sample **107** and/or the sensor **716**. For example, the one or more processors **720** may be configured to adjust the objective lens **706** or one or more optical elements **702** in order to focus illumination **701** from illumination source **100** onto the surface of the sample **107**. By way of another example, the one or more processors **720** may be configured to adjust the objective lens **706** and/or one or more optical elements **710** in order to collect illumination from the surface of the sample **107** and focus the collected illumination on the sensor **716**.

It is noted that the system **700** may be configured in any optical configuration known in the art including, but not limited to, a dark-field configuration, a bright-field orientation, and the like.

Additional details of various embodiments of inspection or metrology system **700** are described in U.S. patent application Ser. No. 13/554,954, entitled "Wafer Inspection System," filed on Jul. 9, 2012; U.S. Published Patent Application 2009/0180176, entitled "Split Field Inspection System Using Small Catadioptric Objectives," published on Jul. 16, 2009; U.S. Published Patent Application 2007/0002465, entitled "Beam Delivery System for Laser Dark-Field Illumination in a Catadioptric Optical System," published on Jan. 4, 2007; U.S. Pat. No. 5,999,310, entitled "Ultra-broadband UV Microscope Imaging System with Wide Range Zoom Capability," issued on Dec. 7, 1999; U.S. Pat. No. 7,525,649 entitled "Surface Inspection System Using Laser Line Illumination with Two Dimensional Imaging," issued on Apr. 28, 2009; U.S. Published Patent Application 2013/0114085, entitled "Dynamically Adjustable Semiconductor Metrology System," by Wang et al. and published on May 9, 2013; U.S. Pat. No. 5,608,526, entitled "Focused Beam Spectroscopic Ellipsometry Method and System" by Piwonka-Corle et al., issued on Mar. 4, 1997; and U.S. Pat. No. 6,297,880, entitled "Apparatus for Analysing Multi-Layer Thin Film Stacks on Semiconductors," by Rosencwaig et al., issued on Oct. 2, 2001, which are each incorporated herein by reference in their entirety.

FIG. **8** illustrates a simplified schematic diagram of an inspection and/or metrology system **800**, in accordance with one or more embodiments of the present disclosure. In one embodiment, system **800** may include multiple measurement and/or inspection subsystems which are configured to implement broadband illumination source **100** as a light source.

In one embodiment, system **800** may include a Beam Profile Ellipsometer (BPE) **810**, a Beam Profile Reflectometer (BPR) **812**, a Broadband Reflective Spectrometer (BRS) **814**, a Broadband Spectroscopic Ellipsometer (BSE) **818**, and a reference ellipsometer **802**. In one embodiment, these optical measurement devices may utilize as few as three optical sources including, but not limited to, lasers **820**, **890**, and illumination source **100**, as described previously herein. The probe beams **824**, **826** are reflected by mirror **830**, and pass through mirror **842** to a sample **107**.

In another embodiment, laser **820** may generate a probe beam **824**, and illumination source **100** may generate probe beam **826** (which is collimated by lens **828** and directed along the same path as probe beam **824** by mirror **829**). In another embodiment, laser **820** may be a solid state laser diode which emits a linearly polarized 3 mW beam at a visible or near IR wavelength such as a wavelength near 670 nm.

In one embodiment, probe beams **824**, **826** are focused onto the surface of the sample **107** via one or more lenses **832**, **833**. Lenses **832**, **833** may be mounted in a turret (not shown) and are alternately movable into the path of probe beams **824**, **826**. Lenses **832**, **833** may include any lens known in the art. For example, lens **832** may be a microscope objective lens with a high numerical aperture (on the order of 0.90 NA) to create a large spread of angles of incidence with respect to the sample surface, and to create a spot size of about one micron in diameter. By way of another example, lens **833** may be a reflective lens having a lower numerical aperture (on the order of 0.1 to 0.4 NA) and capable of focusing broadband light to a spot size of about 5-20 μm. It is noted herein that the use of the term 'lens' in the present disclosure may include curved mirrors and optics that comprise a combination of mirrors and lenses. It is further noted that, because some embodiments of the present disclosure incorporate light sources emitting wavelengths over a spectrum from the UV to the IR, curved mirrors can be conveniently used for focusing the light with minimal chromatic aberration.

Beam profile ellipsometry (BPE) is discussed in U.S. Pat. No. 5,181,080, issued Jan. 19, 1993, which is incorporated herein by reference. In one embodiment, BPE **810** may include a quarter-wave plate **834**, polarizer **836**, lens **838**, and a quad sensor **840**. In another embodiment, linearly polarized probe beam **824** may be focused onto sample **107** by lens **832**. In another embodiment, light reflected from the surface of sample **107** may pass up through lens **832**, mirrors **842**, **830**, **844**, and be directed into BPE **810** by mirror **846**. The positions of the rays within the reflected probe beam correspond to specific angles of incidence with respect to the surface of the sample **107**. In one embodiment, quarter-wave plate **834** may retard the phase of one of the polarization states of the beam by 90 degrees. In another embodiment, linear polarizer **836** may cause the two polarization states of the beam to interfere with each other. For maximum signal, the axis of the polarizer **836** may be oriented at an angle of 45 degrees with respect to the fast and slow axis of the quarter-wave plate **834**. In another embodiment, sensor **840** may be a quad-cell sensor with four radially disposed quadrants. In this regard, each of the four radially disposed quadrants may each intercept one quarter of the probe beam and generate a separate output signal proportional to the power of the portion of the probe beam striking that quadrant. In one embodiment, output signals from each quadrant are sent to one or more processors **848**. As discussed in U.S. Pat. No. 5,181,080, by monitoring the change in the polarization state of the beam, ellipsometric information, such as LP and A, can be determined.

In one embodiment, system **800** may include a beam profile reflectometry (BPR) **812**. Beam profile reflectometry (BPR) is discussed in U.S. Pat. No. 4,999,014, issued on Mar. 12, 1991, which is incorporated herein by reference. In one embodiment, BPR **812** may include a lens **850**, beam splitter **852**, and two linear sensor arrays **854** and **856** to measure the reflectance of the sample **107**. In one embodiment, linearly polarized probe beam **824** may be focused onto sample **107** by lens **832**, with various rays within the beam striking the surface of the sample **107** at a range of angles of incidence. In another embodiment, light reflected from the sample **107** surface may pass up through lens **832**, mirrors **842** and **830**, and be directed into BPR **812** by mirror **844**. The positions of the rays within the reflected probe beam correspond to specific angles of incidence with respect to the surface of the sample **107**. In one embodiment, lens **850** spatially spreads the beam two-dimensionally. In another embodiment, beam splitter **852** may separate the s and p components of the beam. In another embodiment, sensor arrays **854** and **856** may be oriented orthogonal to each other to isolate information about s and p polarized light. It is noted that the higher angles of incidence rays will fall closer to the opposed ends of the arrays. It is further noted that the output from each element in the sensor arrays **854**, **856** will correspond to different angles of incidence.

In another embodiment, sensor arrays **854**, **856** may measure the intensity across the reflected probe beam as a function of the angle of incidence with respect to the sample **107** surface. It is noted herein that sensor arrays **854**, **856** may comprise one or more line sensors. In another embodiment, one or more processors **848** may receive the output of the sensor arrays **854**, **856**, and derive the thickness and refractive index of the thin film layer **808** based on these angular dependent intensity measurements by utilizing various types of modeling algorithms. Optimization routines which use iterative processes such as least square fitting routines are typically employed. One example of this type of optimization routine is described in "Multiparameter Measurements of Thin Films Using Beam-Profile Reflectivity," Fanton et al., Journal of Applied Physics, Vol. 73, No. 11, p.7035, 1993. Another example appears in "Simultaneous Measurement of Six Layers in a Silicon on Insulator Film Stack Using Spectrophotometry and Beam Profile Reflectometry," Leng et al., Journal of Applied Physics, Vol. 81, No. 8, page 3570, 1997. Both of these publications are incorporated herein by reference.

In another embodiment, system **800** may include a broadband reflective spectrometer (BRS) **814**. In one embodiment, BRS **814** may simultaneously probe the sample **107** with multiple wavelengths of light. In another embodiment, BRS **814** may use lenses **832**, **833** to direct light to the surface of the sample **107**. In another embodiment, BRS **814** may include a broadband spectrometer **858**. It is noted that broadband spectrometer **858** may include any broadband spectrometer known in the art. In one embodiment, broadband spectrometer **858** may include a lens **860**, aperture **862**, dispersive element **864**, and sensor array **866**. In one embodiment, probe beam **826** from illumination source **100** may be focused onto sample **107** by lens **832**. Light reflected from the surface of the sample **107** may pass up through lens **832**, and be directed by mirror **842** (through mirror **884**) to broadband spectrometer **858**. In one embodiment, lens **860** may focus the probe beam through aperture **862**, which defines a spot in the field of view on the sample **107** surface to analyze.

In one embodiment, dispersive element **864** (e.g., diffraction grating, prism, holographic plate, and the like) angularly disperses the beam as a function of wavelength to individual sensor elements contained in the sensor array **866**. The different sensor elements may measure the optical intensities of the different wavelengths of light contained in the probe beam. In a preferred embodiment, sensor array **866** comprises a line sensor. In another embodiment, dispersive element **864** may also be configured to disperse the light as a function of wavelength in one direction, and as a function of the angle of incidence with respect to the sample **107** surface in an orthogonal direction, such that simultaneous measurements as a function of both wavelength and angle of incidence are possible. In such an embodiment, sensor array **866** may comprise a line sensor configured so as to simultaneously collect 2 or 3 spectra, each spectrum corresponding to a different range of angles of incidence. In another embodiment, one or more processors **848** may process the intensity information measured by the sensor array **866**. It is noted that, when only a subset of the wavelengths is needed for a specific measurement (e.g., if only visible wavelengths are needed), a refractive lens may be used for the measurements. It is further noted that, when IR and/or UV are needed for a specific measurement, reflective lens **833** may be used instead of focusing lens **832**. In one embodiment, a turret (not shown) containing lenses **832**, **833** may be rotated such that reflective lens **833** is aligned in probe beam **826**. It is noted herein that reflective lens **833** may be necessary because refractive lenses may be unable to focus a wide range of wavelengths onto the sample **107** without substantial chromatic aberration.

In one embodiment, system **800** may include broadband spectroscopic ellipsometry (BSE) **818**. Broadband spectroscopic ellipsometry (BSE) is discussed in U.S. Pat. No. 5,877,859, issued on Mar. 2, 1999 to Aspnes et al., which is incorporated by reference herein. In one embodiment, BSE **818** may include a polarizer **870**, focusing mirror **872**, collimating mirror **874**, rotating compensator **876**, and analyzer **880**. In one embodiment, mirror **882** may direct at least part of probe beam **826** to polarizer **870**, which creates a known polarization state for the probe beam **826**. In a preferred embodiment, the polarization state for the probe beam **826** is a linear polarization. In another embodiment, mirror **872** focuses the beam onto the sample **107** surface at an oblique angle, ideally on the order of 70 degrees to the normal of the sample **107** surface. Based upon well-known ellipsometric principles, the reflected beam will generally have a mixed linear and circular polarization state after interacting with the sample **107**, based upon the composition and thickness of the sample's **107** film **808** and substrate **806**. In another embodiment, reflected beam is collimated by mirror **874**, which directs the beam to the rotating compensator **876**.

In another embodiment, compensator **876** introduces a relative phase delay δ (phase retardation) between a pair of mutually orthogonal polarized optical beam components. In another embodiment, compensator **876** is rotated at an angular velocity ω about an axis substantially parallel to the propagation direction of the beam, preferably by an electric motor **878**. In another embodiment, analyzer **880** mixes the polarization states incident on it. In a preferred embodiment, analyzer **880** is another linear polarizer. By measuring the light transmitted by analyzer **880**, the polarization state of the reflected probe beam **826** may be determined. In another embodiment, mirror **884** directs the beam to spectrometer **858**, which simultaneously measures on sensor **866** the intensities of the different wavelengths of light in the reflected probe beam that pass through the compensator/analyzer combination. In a preferred embodiment, sensor **866** comprises a line sensor. In another embodiment, in order to solve for sample characteristics, such as the ellipsometric values LP and A (as described in U.S. Pat. No. 5,877,859) one or more processors **848** receive the output of the sensor **866**, and processes the intensity information measured by the sensor **866** as a function of wavelength and the azimuth (rotational) angle of the compensator **876** about its axis of rotation.

In one embodiment, detector **886** may be positioned above mirror **846**, and can be used to view reflected beams off of the sample **107** for alignment and focus purposes. It is noted herein that detector **886** may include any detector assembly known in the art.

In one embodiment, in order to calibrate BPE **810**, BPR **812**, BRS **814**, and BSE **818**, system **800** may include the wavelength stable calibration reference ellipsometer **802** that may be used in conjunction with a reference sample **107**. In one embodiment, ellipsometer **802** may include a light source **890**, polarizer **892**, lenses **894**, **896**, rotating compensator **898**, analyzer **803**, and detector **805**.

In one embodiment, light source **890** produces a quasi-monochromatic probe beam **807** having a known stable wavelength and stable intensity. The wavelength of beam **807**, which is a known constant or a measured value, is provided to one or more processors **848** such that ellipsometer **802** can accurately calibrate the optical measurement devices in system **800**.

In another embodiment, beam **807** interacts with polarizer **892** to create a known polarization state. In a preferred embodiment, polarizer **892** is a linear polarizer made from a quartz Rochon prism. However, it is noted that, in general, the polarization does not necessarily have to be linear, nor even complete. Polarizer **892** may also be made from calcite or MgF_2. In one embodiment, the azimuth angle of polarizer **892** is oriented such that the plane of the electric vector associated with the linearly polarized beam exiting from the polarizer **892** is at a known angle with respect to the plane of incidence (defined by the propagation direction of the beam **807** and the normal to the surface of sample **107**). The azimuth angle is preferably selected to be on the order of 30 degrees because the sensitivity is optimized when the reflected intensities of the P and S polarized components are approximately balanced. It is noted herein that polarizer **892** may be omitted if the light source **890** emits light with the desired known polarization state.

In one embodiment, beam **807** is focused onto the sample **107** by lens **894** at an oblique angle. In a preferred embodiment, beam **807** is incident on sample **107** at an angle on the order of 70 degrees to the normal of the sample **107** surface. It is noted herein that sensitivity to sample **107** properties is maximized in the vicinity of the Brewster or pseudo-Brewster angle of a material. Based upon well-known ellipsometric principles, the reflected beam will generally have a mixed linear and circular polarization state after interacting with the sample **107**, as compared to the linear polarization state of the incoming beam **807**.

In another embodiment, lens **896** collimates beam **807** after its reflection off the sample **107**. In another embodiment, beam **807** then passes through the rotating compensator (retarder) **898**, which introduces a relative phase delay Or (phase retardation) between a pair of mutually orthogonal polarized optical beam components. The amount of phase retardation is a function of the wavelength, the dispersion characteristics of the material used to form the compensator, and the thickness of the compensator. In one embodiment, compensator **898** is rotated at an angular velocity ωr about an axis substantially parallel to the propagation direction of beam **807**, preferably by an electric motor **801**. It is noted that compensator **898** may include any conventional wave-plate compensator known in the art. For example, the compensator may include a wave-plate compensator made of crystal quartz. The thickness and material of the compensator **898** may be selected such that a desired phase retardation of the beam is induced. Typically, a phase retardation of about 90° is convenient.

In another embodiment, beam **807** interacts with analyzer **803**, which serves to mix the polarization states incident on it. In this embodiment, analyzer **803** is another linear polarizer, preferably oriented at an azimuth angle of 45 degrees relative to the plane of incidence. However, it is noted that any optical device that serves to appropriately mix the incoming polarization states can be used as an analyzer **803**. In a preferred embodiment, analyzer **803** is a quartz Rochon or Wollaston prism.

It is noted herein that compensator **898** may be located either between the sample **107** and the analyzer **803** (as shown in FIG. **8**). Alternatively, compensator **898** may be located between the sample **107** and the polarizer **892**. It is further noted that polarizer **870**, lenses **894**, **896**, compensator **898**, and analyzer **803** may all be optimized in their construction for the specific wavelength of light produced by light source **890**, which maximizes the accuracy of ellipsometer **802**.

In another embodiment, beam **807** may enter detector **805**, which measures the intensity of the beam passing through the compensator/analyzer combination. In another embodiment, one or more processors **848** process the intensity information measured by the detector **805** to determine the polarization state of the light after interacting with the analyzer **803**, and therefore the ellipsometric parameters of the sample **107**. This information processing may include measuring beam intensity as a function of the azimuth (rotational) angle of the compensator about its axis of rotation. This measurement of intensity as a function of compensator rotational angle is effectively a measurement of the intensity of beam **807** as a function of time, since the compensator angular velocity is usually known and constant.

U.S. Pat. No. 6,297,880, which issued on Oct. 2, 2001 to Rosenecwaig et al. and is incorporated by reference herein, describes metrology system **800** in further detail. U.S. Pat. No. 6,429,943, which issued on Aug. 6, 2002 to Opsal et al. and is incorporated by reference herein, describes how metrology system **800** may be used for scatterometry measurements. U.S. Pat. No. 5,608,526, which issued on Mar. 4, 1997 to Piwonka-Corle et al. and is incorporated by reference herein, describes an alternative embodiment of metrology system **800** that incorporates a spectroscopic ellipsometer and a spectrophotometer. Either, or both, of the spectroscopic ellipsometer and spectrophotometer may incorporate the broadband illumination source described herein and may be used in methods of measuring a sample described herein.

The one or more processors **720**, **848** of the present disclosure may include any one or more processing elements known in the art. In this sense, the one or more processors **720**, **848** may include any microprocessor-type device configured to execute software algorithms and/or instructions. In one embodiment, the one or more processors **720**, **848** may consist of a desktop computer, mainframe computer system, workstation, image computer, parallel processor, or other computer system (e.g., networked computer) configured to execute a program configured to operate the systems **100**, **700**, **800**, as described throughout the present disclosure. It should be recognized that the steps described throughout the present disclosure may be carried out by a single computer system or, alternatively, multiple computer systems. In general, the term "processor" may be broadly defined to encompass any device having one or more processing elements, which execute program instructions from a non-transitory memory medium **722**. Moreover, different subsystems of the various systems disclosed may include processor or logic elements suitable for carrying out at least a portion of the steps described throughout the present disclosure. Therefore, the above description should not be interpreted as a limitation on the present disclosure but merely an illustration.

The memory medium **722** may include any storage medium known in the art suitable for storing program instructions executable by the associated one or more processors **720**. For example, the memory medium **722** may include a non-transitory memory medium. For instance, the memory medium **722** may include, but is not limited to, a read-only memory, a random access memory, a magnetic or optical memory device (e.g., disk), a magnetic tape, a solid state drive, and the like. In another embodiment, the memory **722** is configured to store one or more results and/or outputs of the various steps described herein. It is further noted that memory **722** may be housed in a common controller housing with the one or more processors **720**. In an alternative embodiment, the memory **722** may be located remotely with respect to the physical location of the processors **720**. For instance, the one or more processors **720** may access a remote memory (e.g., server), accessible through a network (e.g., internet, intranet, and the like). In another embodiment, the memory medium **722** maintains program instructions for causing the one or more processors **720** to carry out the various steps described through the present disclosure.

In another embodiment, the systems **100**, **700**, **800** may include a user interface (not shown). In one embodiment, the user interface is communicatively coupled to the one or more processors **720**, **848**. In another embodiment, the user interface device may be utilized to accept selections and/or instructions from a user. In some embodiments, described further herein, a display may be used to display data to a user. In turn, a user may input selection and/or instructions (e.g., selection, sizing, and/or position of filter box) responsive to data displayed to the user via the display device.

The user interface device may include any user interface known in the art. For example, the user interface may include, but is not limited to, a keyboard, a keypad, a touchscreen, a lever, a knob, a scroll wheel, a track ball, a switch, a dial, a sliding bar, a scroll bar, a slide, a handle, a touch pad, a paddle, a steering wheel, a joystick, a bezel mounted input device, or the like. In the case of a touchscreen interface device, those skilled in the art should recognize that a large number of touchscreen interface devices may be suitable for implementation in the present invention. For instance, the display device may be integrated with a touchscreen interface, such as, but not limited to, a capacitive touchscreen, a resistive touchscreen, a surface acoustic based touchscreen, an infrared based touchscreen, or the like. In a general sense, any touchscreen interface capable of integration with the display portion of a display device is suitable for implementation in the present disclosure.

The display device may include any display device known in the art. In one embodiment, the display device may include, but is not limited to, a liquid crystal display (LCD), an organic light-emitting diode (OLED) based display or a CRT display. Those skilled in the art should recognize that a variety of display devices may be suitable for implementation in the present disclosure and the particular choice of display device may depend on a variety of factors, including, but not limited to, form factor, cost, and the like. In a general sense, any display device capable of integration with a user interface device (e.g., touchscreen, bezel mounted interface, keyboard, mouse, trackpad, and the like) is suitable for implementation in the present disclosure.

In some embodiments, the systems **100**, **700**, **800**, as described herein, may be configured as a "stand alone tool" or a tool that is not physically coupled to a process tool. In other embodiments, such an inspection or metrology system may be coupled to a process tool (not shown) by a transmission medium, which may include wired and/or wireless portions. The process tool may include any process tool known in the art such as a lithography tool, an etch tool, a deposition tool, a polishing tool, a plating tool, a cleaning tool, or an ion implantation tool. The results of inspection or measurement performed by the systems described herein may be used to alter a parameter of a process or a process tool using a feedback control technique, a feedforward control technique, and/or an in-situ control technique. The parameter of the process or the process tool may be altered manually or automatically.

The embodiments of the systems **100**, **700**, **800** may be further configured as described herein. In addition, the systems **100**, **700**, **800** may be configured to perform any other step(s) of any of the method embodiment(s) described herein.

FIG. **9** illustrates a flow diagram depicting a method for generating broadband illumination, in accordance with one or more embodiments of the present disclosure. It is noted herein that the steps of method **900** may be implemented all or in part by systems **100**, **700**, or **800**. It is further recognized, however, that the method **900** is not limited to the systems **100**, **700**, or **800**, in that additional or alternative system-level embodiments may carry out all or part of the steps of method **900**.

In step **902**, one or more pump beams are generated. For example, as shown in FIGS. **1-2**, one or more pump lasers may be used to generate one or more pump beams **103**.

In step **904**, the one or more pump beams are directed into an active medium containing one or more nanocrystals. For example, as shown in FIGS. **1-2**, one or more pump illumination optics **108** (e.g., mirror, lens, etc.) are used to direct and/or focus the one or more pump beams into the active medium **104**.

In step **906**, the nanocrystals contained within (or form) the active medium **104** down-convert the illumination of the one or more pump beams into broadband illumination. For example, as shown in FIGS. **1-2**, the active medium down-converts the illumination from the one or more pump beams to generate down-converted illumination that is red-shifted relative to the illumination of the one or more pump beams **103**.

In step **908**, the down-converted illumination is collected from the active medium **104**. For example, as shown in FIG. **2**, one or more collection optics **110** serve to collect at least a portion of the down-converted broadband emission **105** from the active medium **104**. In turn, the collection optics **110** may further be used to direct the broadband emission **105** to one or more additional optics (e.g., input optics for an inspection tool or metrology tool).

The herein described subject matter sometimes illustrates different components contained within, or connected with, other components. It is to be understood that such depicted architectures are merely exemplary, and that in fact many other architectures can be implemented which achieve the same functionality. In a conceptual sense, any arrangement of components to achieve the same functionality is effectively "associated" such that the desired functionality is achieved. Hence, any two components herein combined to achieve a particular functionality can be seen as "associated with" each other such that the desired functionality is achieved, irrespective of architectures or intermedial components. Likewise, any two components so associated can also be viewed as being "connected," or "coupled," to each other to achieve the desired functionality, and any two components capable of being so associated can also be viewed as being "couplable," to each other to achieve the desired functionality. Specific examples of couplable include but are not limited to physically mateable and/or physically interacting components and/or wirelessly interactable and/or wirelessly interacting components and/or logically interacting and/or logically interactable components.

Furthermore, it is to be understood that the invention is defined by the appended claims. It will be understood by those within the art that, in general, terms used herein, and especially in the appended claims (e.g., bodies of the appended claims) are generally intended as "open" terms (e.g., the term "including" should be interpreted as "including but not limited to," the term "having" should be interpreted as "having at least," the term "includes" should be interpreted as "includes but is not limited to," etc.). It will be further understood by those within the art that if a specific number of an introduced claim recitation is intended, such an intent will be explicitly recited in the claim, and in the absence of such recitation no such intent is present. For example, as an aid to understanding, the following appended claims may contain usage of the introductory phrases "at least one" and "one or more" to introduce claim recitations. However, the use of such phrases should not be construed to imply that the introduction of a claim recitation by the indefinite articles "a" or "an" limits any particular claim containing such introduced claim recitation to inventions containing only one such recitation, even when the same claim includes the introductory phrases "one or more" or "at least one" and indefinite articles such as "a" or "an" (e.g., "a" and/or "an" should typically be interpreted to mean "at least one" or "one or more"); the same holds true for the use of definite articles used to introduce claim recitations. In addition, even if a specific number of an introduced claim recitation is explicitly recited, those skilled in the art will recognize that such recitation should typically be interpreted to mean at least the recited number (e.g., the bare recitation of "two recitations," without other modifiers, typically means at least two recitations, or two or more recitations). Furthermore, in those instances where a convention analogous to "at least one of A, B, and C, etc." is used, in general such a construction is intended in the sense one having skill in the art would understand the convention (e.g., "a system having at least one of A, B, and C" would include but not be limited to systems that have A alone, B alone, C alone, A and B together, A and C together, B and C together, and/or A, B, and C together, etc.). In those instances where a convention analogous to "at least one of A, B, or C, etc." is used, in general such a construction is intended in the sense one having skill in the art would understand the convention (e.g., "a system having at least one of A, B, or C" would include but not be limited to systems that have A alone, B alone, C alone, A and B together, A and C together, B and C together, and/or A, B, and C together, etc.). It will be further understood by those within the art that virtually any disjunctive word and/or phrase presenting two or more alternative terms, whether in the description, claims, or drawings, should be understood to contemplate the possibilities of including one of the terms, either of the terms, or both terms. For example, the phrase "A or B" will be understood to include the possibilities of "A" or "B" or "A and B."

It is believed that the present disclosure and many of its attendant advantages will be understood by the foregoing description, and it will be apparent that various changes may be made in the form, construction, and arrangement of the components without departing from the disclosed subject matter or without sacrificing all of its material advantages. The form described is merely explanatory, and it is the intention of the following claims to encompass and include such changes. Furthermore, it is to be understood that the invention is defined by the appended claims.

The invention claimed is:

1. A broadband illumination source comprising:

a pump source configured to generate pump illumination;

an active medium containing a plurality of nanocrystals; and

one or more pump illumination optics,

wherein the one or more pump illumination optics are configured to direct pump illumination into the active medium,

wherein the active medium is configured to emit broadband illumination by down converting a portion of the pump illumination via photoluminescence, wherein the active media has an index of refraction suitable to establish a wave guide mode within a cylindrical volume of the active media for the pump illumination, wherein the pump illumination and the emitted broadband illumination are transmitted along an elongated volume of the active medium.

2. The broadband illumination source of claim **1**, further comprising:

one or more collection optics configured to collect a portion of the broadband illumination from the active medium and direct the broadband illumination to one or more additional optical elements.

3. The broadband illumination source of claim **1**, wherein the pump source comprises:

one or more lasers.

4. The broadband illumination source of claim **3**, wherein the one or more lasers comprise:

one or more lasers configured to generate visible light.

5. The broadband illumination source of claim **4**, wherein the one or more lasers comprise:

at least one of a green laser or a blue laser.

6. The broadband illumination source of claim **1**, wherein the broadband illumination emitted by the plurality of nanocrystals comprises:

at least one of visible light or near infrared light.

7. The broadband illumination source of claim **1**, wherein the plurality of nanocrystals comprises:

a plurality of at least one of CdSe nanocrystals, CdS nanocrystals, PbS nanocrystals, ZnSe nanocrystals, or CdTe nanocrystals.

8. The broadband illumination source of claim **1**, wherein the plurality of nanocrystals comprises:

a plurality of core-shell nanocrystals.

9. The broadband illumination source of claim **1**, wherein the plurality of nanocrystals comprises:

a mixture of two or more nanocrystal materials.

10. The broadband illumination source of claim **1**, wherein the plurality of nanocrystals are formed within the active medium in a plurality of monolayers.

11. The broadband illumination source of claim **1**, wherein the plurality of nanocrystals are formed with a surface density between approximately 1×10^{12} and 1×10^{14} nanocrystals/mm^2.

12. The broadband illumination source of claim **1**, wherein at least some of the plurality of nanocrystals have an average size between approximately 1 and 10 nm.

13. The broadband illumination source of claim **1**, wherein the pump illumination optics comprise:

at least one of a mirror or a lens.

14. The broadband illumination source of claim **1**, wherein the active medium comprises:

a volume of liquid material, wherein the active medium is at least one of a solution, a suspension, or a colloid.

15. The broadband illumination source of claim **1**, wherein the active medium comprises:

a glass, wherein the plurality of nanocrystals are formed in a matrix of the glass.

16. The broadband illumination source of claim **1**, wherein the active medium comprises:

a sol-gel material, wherein the plurality of nanocrystals are formed in a matrix of the sol-gel material.

17. The broadband illumination source of claim **1**, wherein the active medium comprises:

a solid material, wherein the plurality of nanocrystals are disposed on or within the solid material.

18. The broadband illumination source of claim **17**, wherein the active medium comprises:

a solid substrate, wherein the plurality of nanocrystals are disposed on the solid substrate.

19. The broadband illumination source of claim **17**, wherein the active medium comprises:

one or more fibers impregnated with the plurality of nanocrystals.

20. The broadband illumination source of claim **1**, wherein the active medium has a cylindrical shape.

21. The broadband illumination source of claim **20**, wherein the pump illumination is transversely directed into the active medium.

22. The broadband illumination source of claim **20**, wherein the pump illumination is longitudinally directed into the active medium.

23. The broadband illumination source of claim **1**, wherein the pump illumination is focused into liquid jet of the active medium.

24. The broadband illumination source of claim **1**, wherein the pump illumination is focused into a capillary structure containing the active medium.

25. The broadband illumination source of claim **1**, wherein the pump illumination is focused into a dye cell containing the active medium.

26. The broadband illumination source of claim **1**, wherein the pump illumination is coupled to the active medium through an end portion of the elongated volume of the active medium.

27. The broadband illumination source of claim **1**, wherein the pump illumination is coupled to the active medium through a coupling element disposed along the elongated volume of the active medium.

28. The broadband illumination source of claim **1**, further comprising:

one or more thermal management devices.

29. The broadband illumination source of claim **28**, wherein the one or more thermal management devices are configured to move at least a portion of the active medium relative to the pump illumination in order to control a local temperature of the active medium.

30. The broadband illumination source of claim **28**, wherein the one or more thermal management devices comprises:

a movable substrate, wherein the active medium is formed on the movable substrate.

31. The broadband illumination source of claim **30**, wherein the movable substrate comprises:

at least one of a rotatable disk, a rotatable drum, a rotatable ring, or a conveyor.

32. The broadband illumination source of claim **28**, wherein the one or more thermal management devices comprises:

one or more fluid transport devices, wherein the active medium is formed within a fluid, wherein the fluid is transported by the one or more fluid transport devices.

33. The broadband illumination source of claim **1**, wherein the pump source comprises:

a plurality of pump lasers, wherein each laser emits pump illumination at a different wavelength.

34. The broadband illumination source of claim **33**, wherein pump illumination from each pump laser is focused into a portion of the active medium to create a plurality of emission regions, wherein each emission region emits broadband illumination of a different wavelength range.

35. The broadband illumination source of claim **34**, wherein the direction of collection of broadband illumination from the plurality of emission regions is perpendicular to the direction of the pump illumination from the plurality of pump lasers.

36. The broadband illumination source of claim **34**, wherein the plurality of emission regions in the active medium are formed with a plurality of nanocrystal species, wherein each emission region corresponds to a particular nanocrystal species.

37. The broadband illumination source of claim **36**, wherein the plurality of emission regions are arranged such that a first emission region emits illumination of a first wavelength range and is located on a side of a collecting path nearest collection optics, wherein an at least an additional emission region emits illumination of an additional wavelength range, wherein a central wavelength of the first wavelength range is shorter than a central wavelength of the first wavelength range.

38. The broadband illumination source of claim **37**, wherein the first emission region is at least partially transparent to illumination emitted by the at least the additional emission region.

39. The broadband illumination source of claim **37**, wherein a size of the nanocrystals of the first emission region is smaller than a size of the nanocrystals of the at least the additional emission region.

40. An optical characterization system comprising:

a broadband illumination source, wherein the broadband illumination source comprises:

a pump source configured to generate pump illumination;

an active medium containing a plurality of nanocrystals; and

one or more pump illumination optics configured to direct pump illumination into the active medium, wherein the active medium is configured to emit broadband illumination by down converting a portion of the pump illumination via photoluminescence, wherein the active media has an index of refraction suitable to establish a wave guide mode within a cylindrical volume of the active media for the pump illumination, wherein the pump illumination and the emitted broadband illumination are transmitted along an elongated volume of the active medium, wherein the optical characterization system further comprises:

one or more source collection optics configured to collect a portion of the broadband illumination from the active medium;

a detector assembly; and

a set of characterization optics configured to direct the broadband illumination from the broadband illumination source onto a sample, wherein the set of characterization optics is further configured to direct illumination from the sample to the detector assembly.

41. A method comprising:

generating a pump beam;

directing the pump beam into an active medium containing a plurality of nanocrystals;

generating broadband illumination by down-converting a portion of pump illumination with the plurality of nanocrystals via photoluminescence, wherein the active media has an index of refraction suitable to establish a wave guide mode within a cylindrical volume of the active media for the pump illumination, wherein the pump illumination and the generated broadband illumination are transmitted along an elongated volume of the active medium;

collecting down-converted broadband illumination from the active medium; and

performing at least one of inspection or metrology on a sample with the collected down-converted broadband illumination.

42. The optical characterization system of claim **40**, wherein the optical characterization system is configured as at least one of an inspection system or a metrology system.

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